CP violation at CDF

Outline

- Standard Model, physics beyond SM (BSM or NP) and the role of indirect searches for BSM.
  - CP violation in b-hadron decays as a tool to search for BSM
- Tevatron and CDF II detector
  - doing *B* physics in hadronic environment
- CP violation measurements at CDF:
  - $B_s \rightarrow J/\psi\phi$: lifetime, $\Delta\Gamma_s$ and CP violation in B_s system
  - charge asymmetry in semileptonic B_s decays
  - CPV in fully hadronic channels
    - $B_s \rightarrow K\pi$, $B^0 \rightarrow K\pi$, and $\Lambda_b \rightarrow p\,\pi$, pK decays
    - $B^+ \rightarrow D^0_{CP}K^+$
- Conclusions

Role of precision measurements

- Standard Model works well: excellent agreement with data for 30+ years.
- Perhaps too well: we don't understand many things (dark matter, dark energy, neutrino masses, baryon asymmetry, no Higgs yet, etc.)
- We all believe there's deeper physics that underlies SM
  - Beyond SM ("BSM"), or New Physics ("NP")
- Road to New Physics:
  - direct searches at Tevatron (now) and LHC (soon)
  - indirect searches: check internal consistency of SM

CP violation as `precision' tests

- If there were New Physics:

$$A_{\mathrm{meas}} = A^{SM} + A^{NP} = |A^{SM}| e^{i\phi^{SM}} + |A^{NP}| e^{i\phi^{NP}}$$

- New Physics can affect the magnitude, i.e. $|A_{\mathrm{meas}}|^2 \neq |A^{SM}|^2$
- Or if there's phase difference, i.e., $\phi^{SM} \neq \phi^{NP}$, there will be ***interference*** which would be *a new source of CP violation*

- CP violation is any difference between properties of a decay and its "mirror image" resulting from C and P transformations. It could include:
  - decay rate (this requires A^{SM} to also contain a strong phase)
  - triple products (works even when strong phase is 0)
  - coefficients describing angular decomposition of the amplitude, etc.

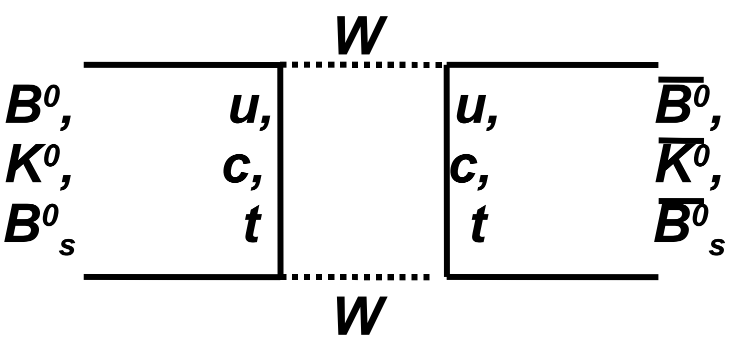
CP violation where there should be none

- Most consistency checks (especially in electroweak data) have achieved amazing precision (think of W mass)
- `Null' measurements (in cases where SM predicts ~ 0) are especially powerful
  - e.g., BR($B_s \to \mu\mu$) in SUSY may be significantly larger than in SM
- CP violation measurements often have lower precision
- So, null CP violation measurements are particularly useful – any *significant* deviation from 0 is a potential signal of BSM
- Null CP violation is the main topic of this talk

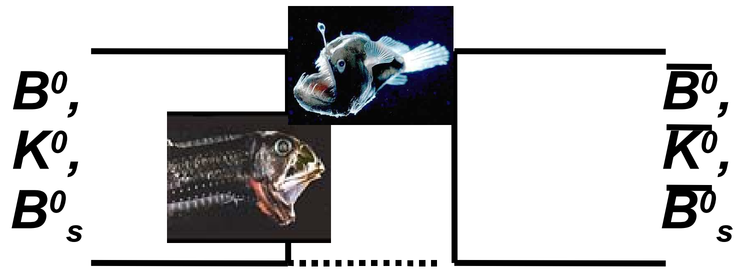
Example of possible NP contribution

New physics, if any, in suppressed processes, as flavor-mixing (or FCNC).

STANDARD MODEL



NEW PHYSICS



Effective field theory factorizes New Physics into a complex amplitude

$$\frac{\langle M|H_{\rm eff}^{\rm full}|\bar{M}\rangle}{\langle M|H_{\rm eff}^{\rm SM}|\bar{M}\rangle} = C_M e^{2i\phi_M}$$

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP}-\beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}} = \frac{\langle B_s|H_{\rm eff}^{\rm full}|\bar{B}_s\rangle}{\langle B_s|H_{\rm eff}^{\rm SM}|\bar{B}_s\rangle},$$

Bottom line: to constrain NP need to measure <u>magnitude and phase</u>

CP violation in Standard Model

- Standard Model CP violation occurs through complex phases in the unitary CKM quark mixing matrix (3 real params + one phase)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Expanded in $\lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.23$:

Large CP violation ~ λ^3

Highly suppressed CP violation ~ λ^5

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

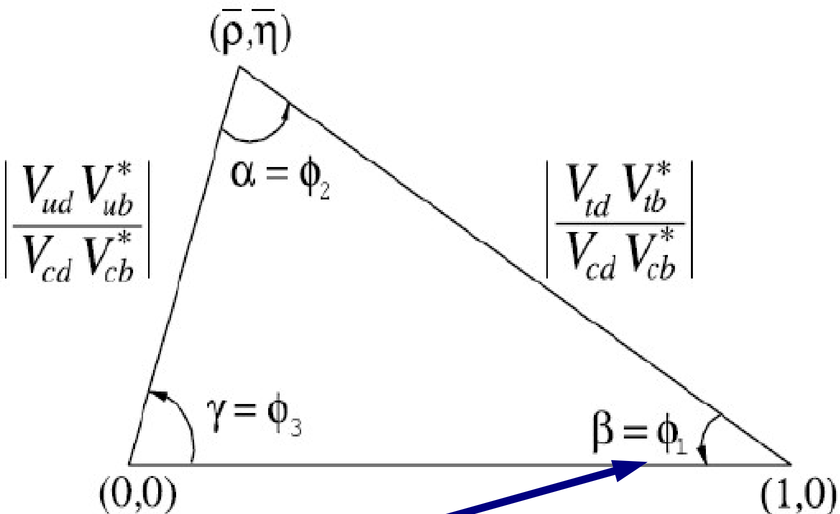
Large CP violation ~ λ^3

Suppressed CP violation ~ λ^4

CP violation in Standard Model (2)

B_d unitarity triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



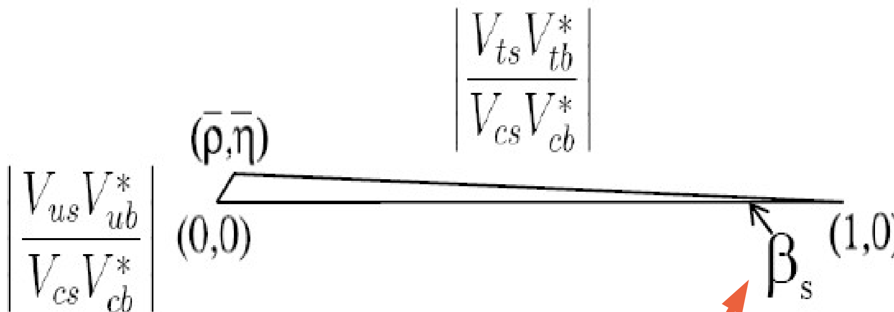
All three angles large

==> $\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$ ~ 22^0

==> Acp large

B_s unitarity triangle

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



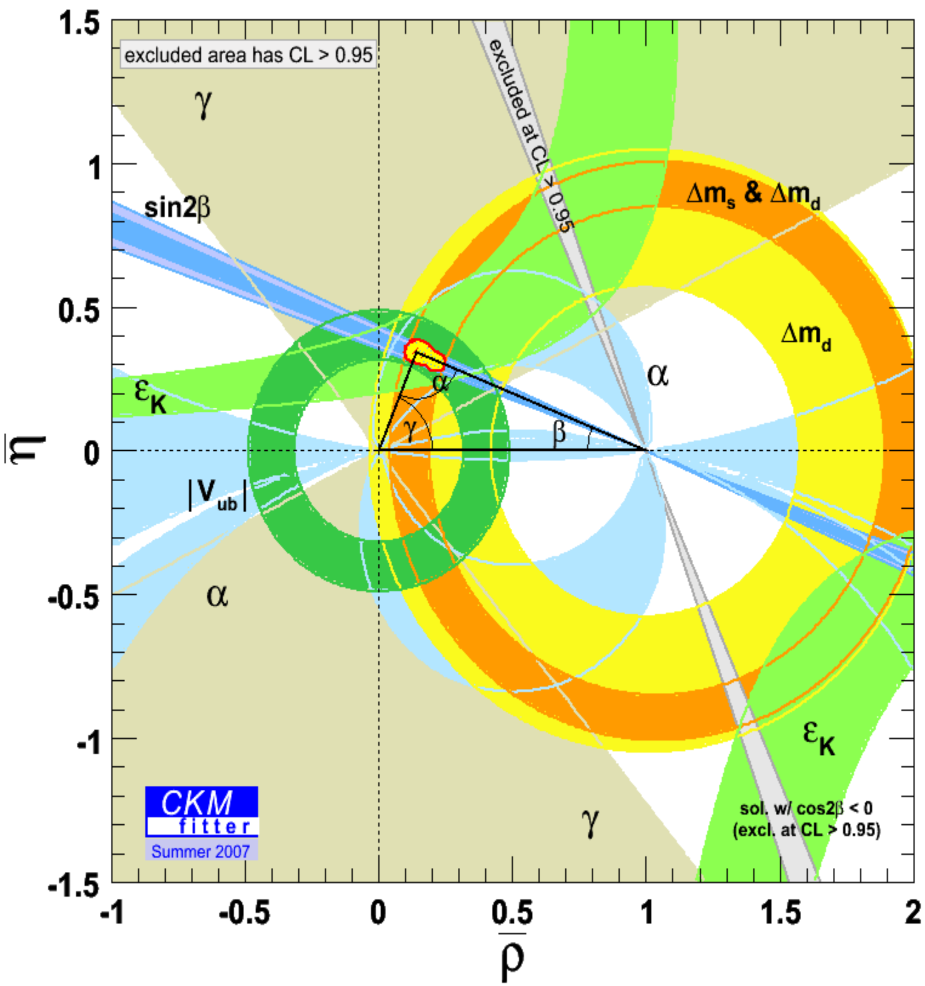
`Squashed' triangle ==> small β_s angle

$$\beta_s = \beta' \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = \mathcal{O}(\lambda^2) \sim 1.1^0$$

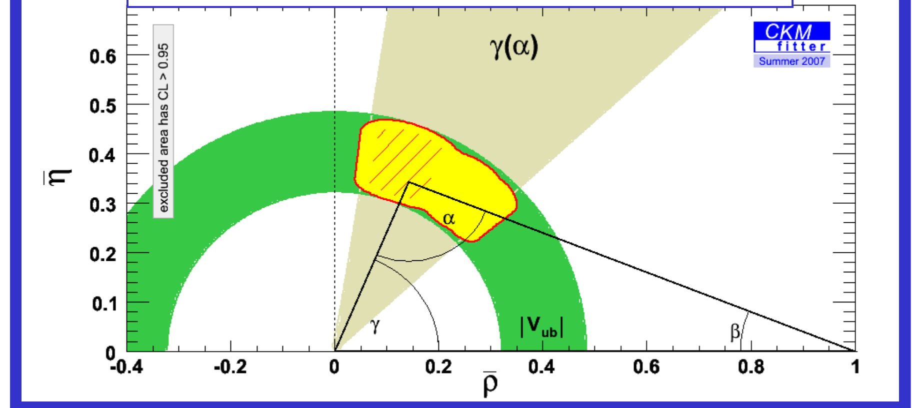
==> Acp ~ 0

Current status – all measurements

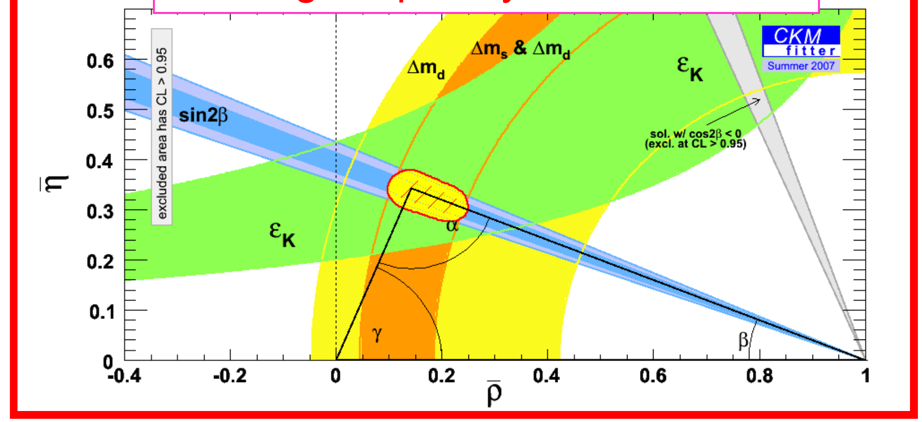
Kaon physics and *B* factories: satisfactory SM picture of CP violation - at least at tree level in B^0 and B^+ decays.



Using 'tree'-only observables

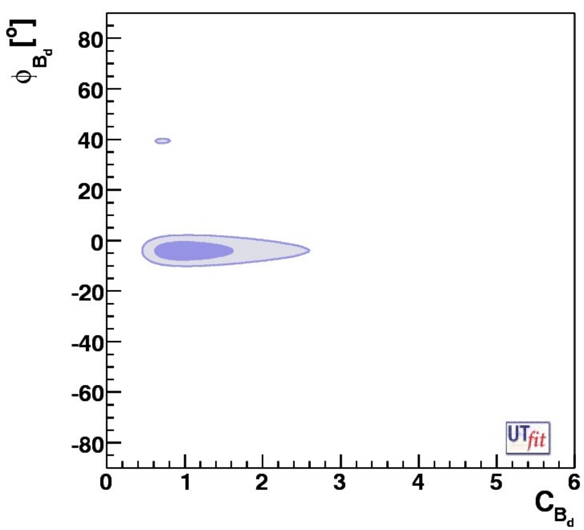


Using 'loop'-only observables

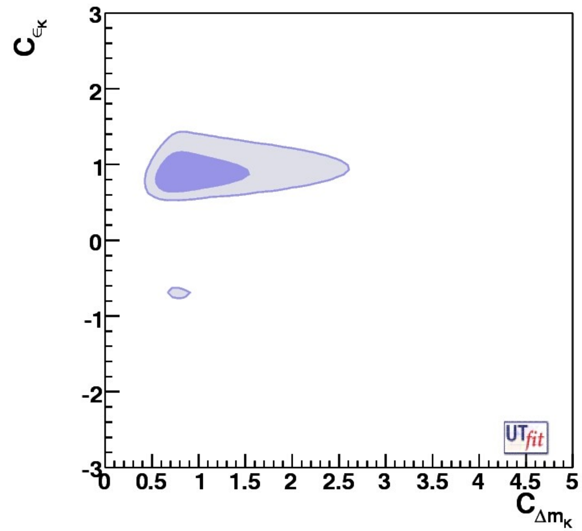


Current status – phases in mixing

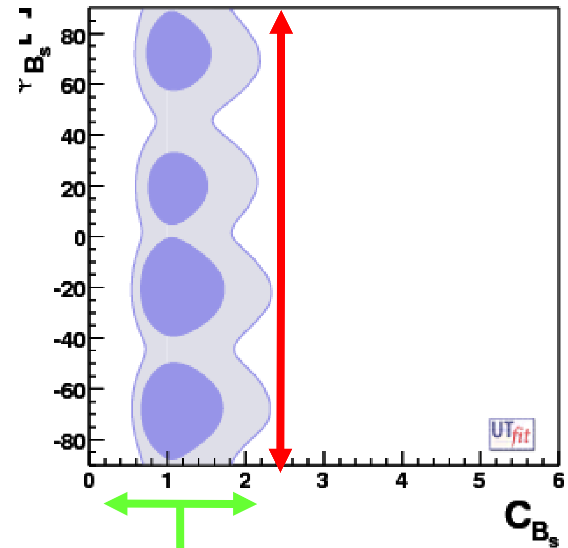
B⁰ mixing



K⁰ mixing



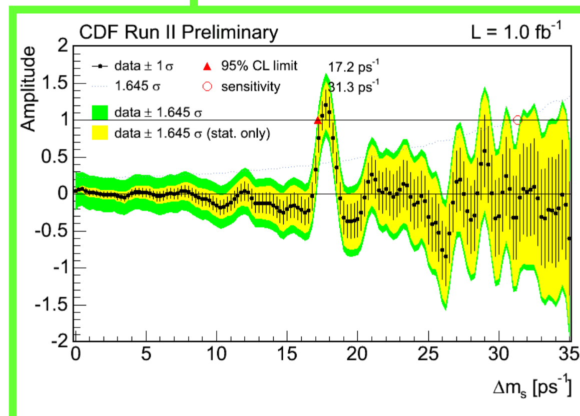
B^0_s mixing



Lattice-QCD dominated uncertainty

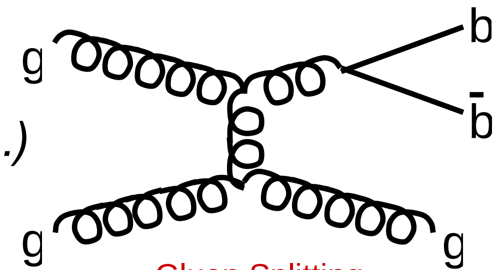
$$\frac{\langle M|H_{\rm eff}^{\rm full}|\bar{M}\rangle}{\langle M|H_{\rm eff}^{\rm SM}|\bar{M}\rangle} = C_M e^{2i\phi_M}$$

Experimentally-dominated uncertainty. This measurement is today's topic

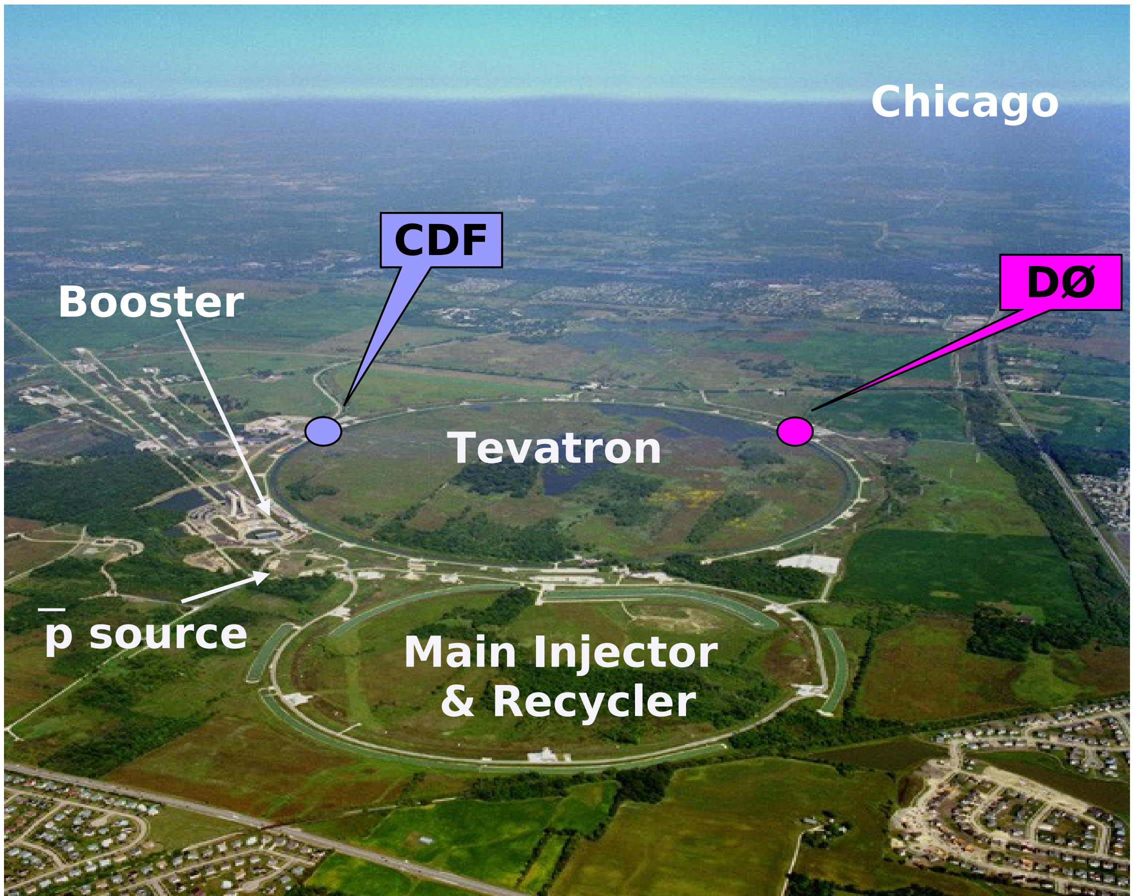


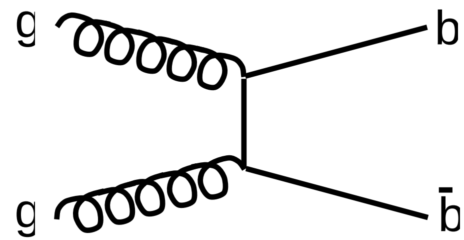
Tevatron + CDF = *b-hadron factory*

- Tevatron: *$p\bar{p}$ collisions at 1.96 GeV/c^2*
- *All species of b-hadrons produced! (B^+, B^0, B_s, B_c, Λ_b, Ξ_b, Σ_b…)*
- performs really well: ~ 3 fb^{-1} data on tape

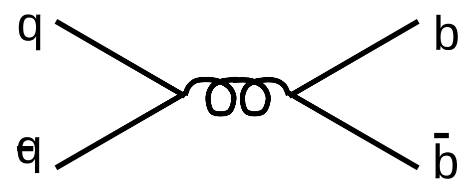


Gluon Splitting

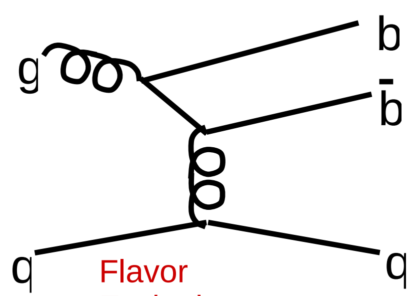




Flavor Creation (gluon fusion)



Flavor Creation (annihilation)

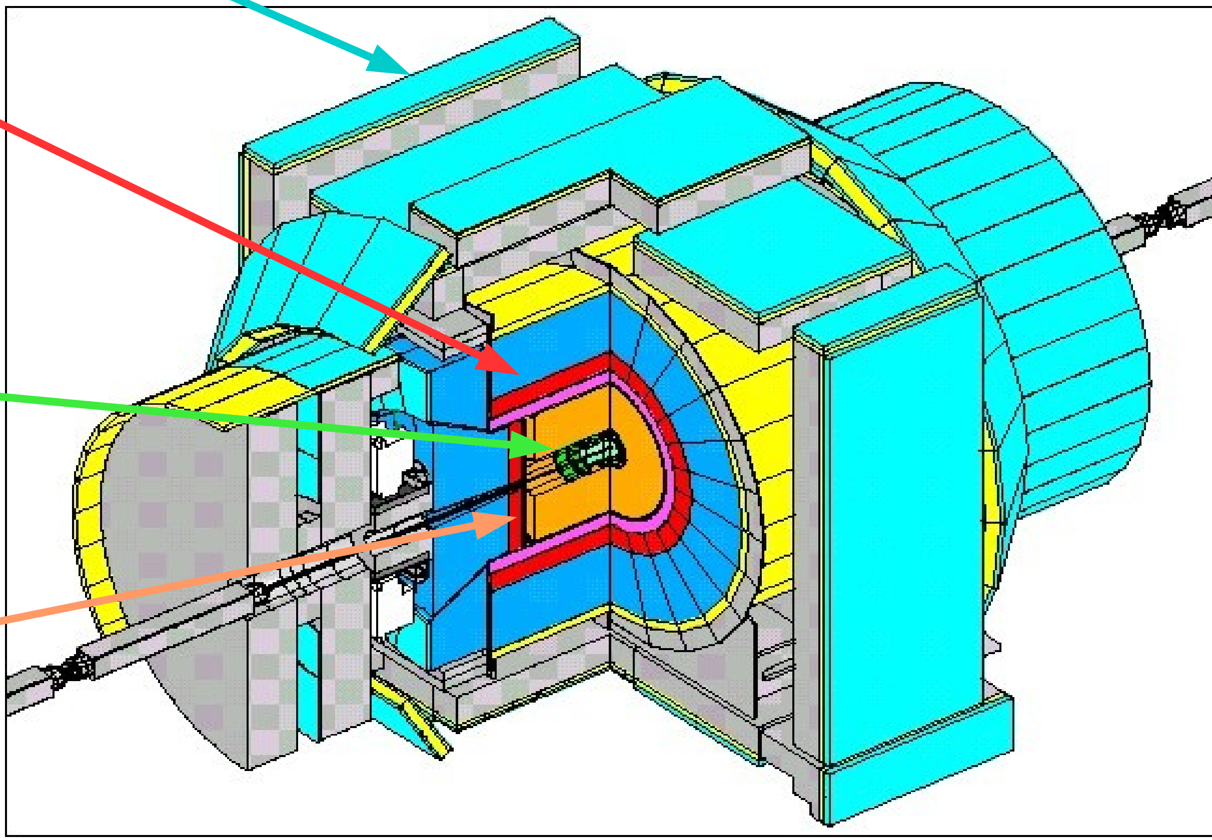


Flavor Excitation

Petar Maksimovic, JHU

Relevant subsystems of CDF

- **muons (for B reconstruction) up to $|\eta| < 1$ (high-η muons used for flavor tagging)**
- central electrons used for B reco, soft electrons also used for flavor tagging

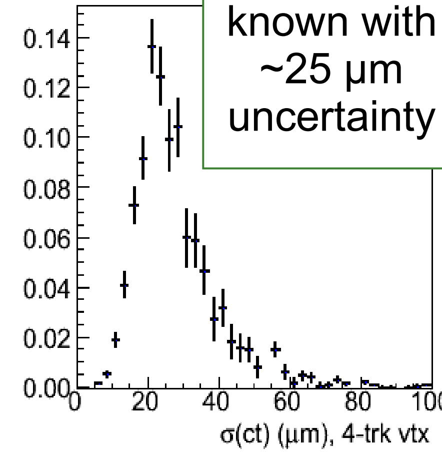


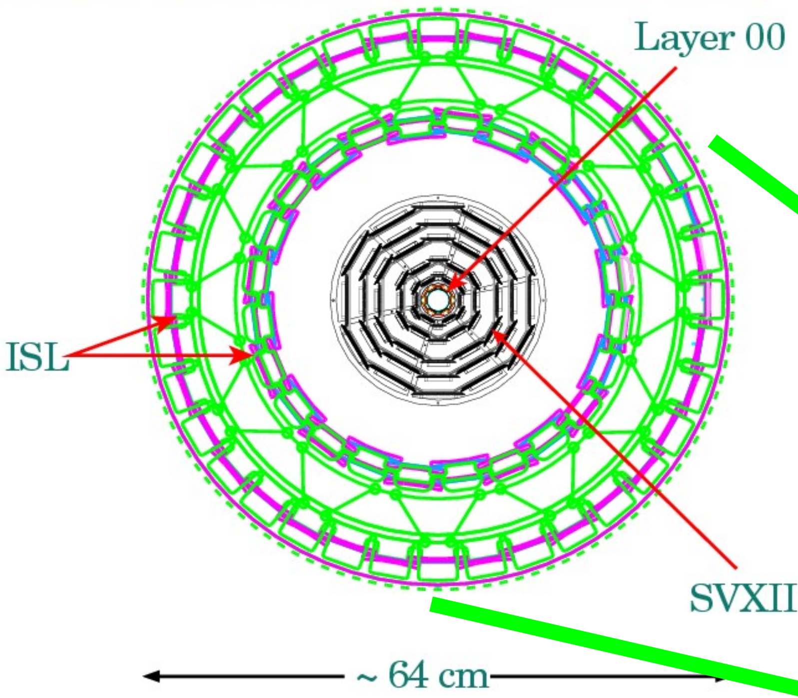
- CDF has excellent tracking:
  - **d_0 resolution (needed for B physics)**
  - **p_T resolution (needed to measure masses)**

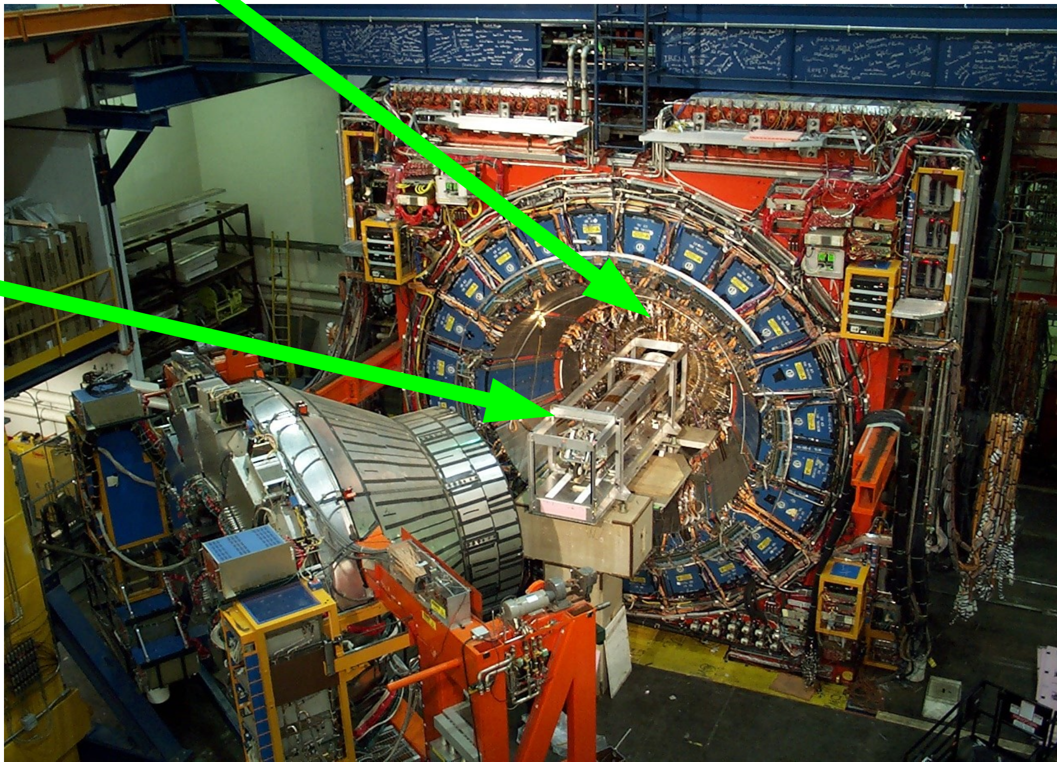
Reconstructing heavy hadrons

B decay position known with ~25 μm uncertainty

- b-quarks CDF can reconstruct are boosted sideways
- $ct = L_{xy}\,(m/p_T)$







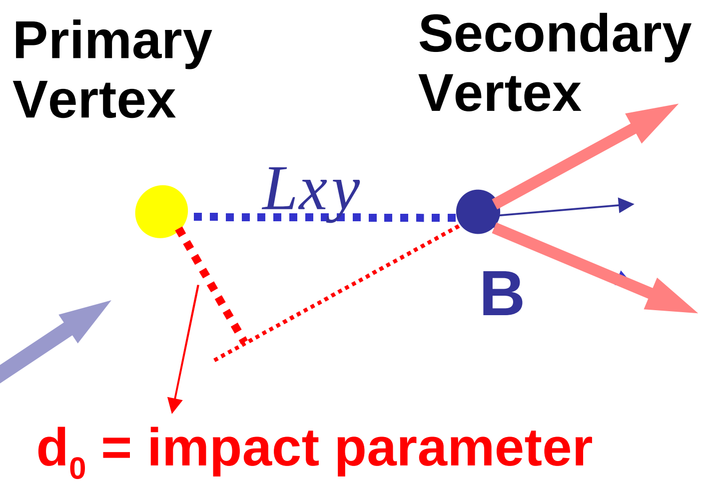
- Decays of hadrons with b and c quarks can be observed with a ***Silicon Detector***

Mining *b*'s from mountains of junk!

- Production rate of b-quarks is very large...
  but rate of (uninteresting) soft QCD is 1000x larger!

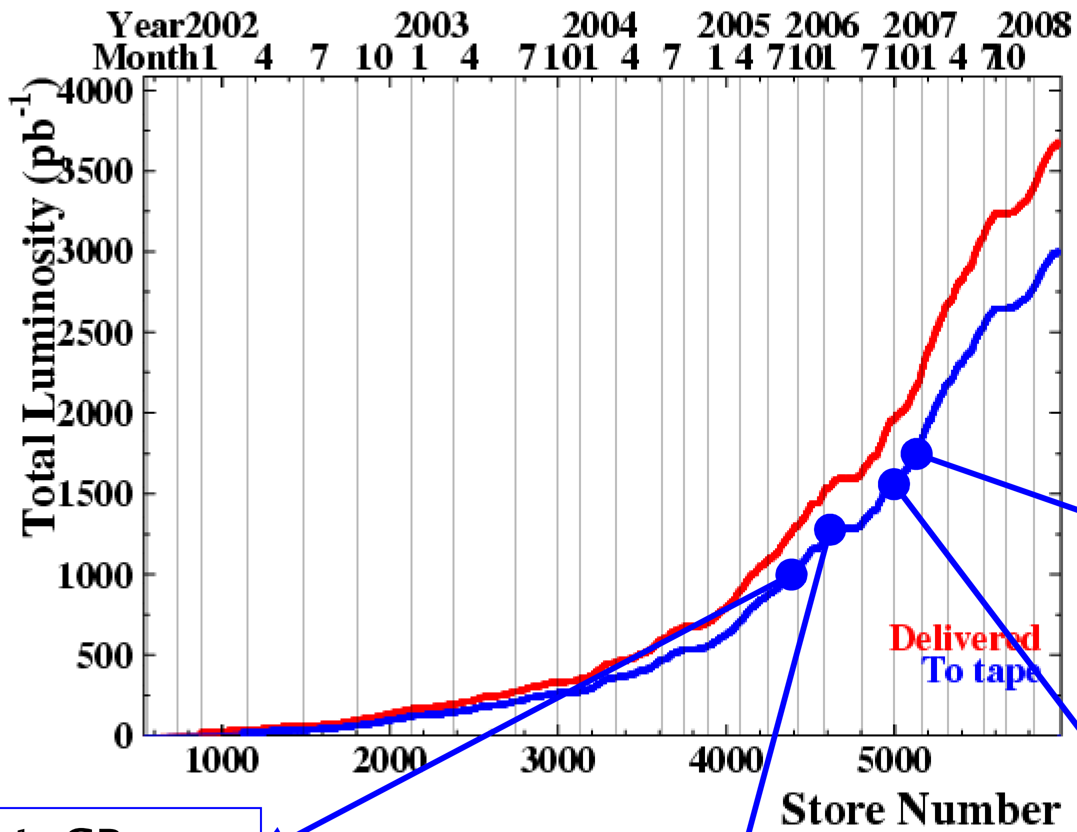
- *b*-physics program lives and dies by the "trigger system"
  - very fast electronics
  - examines events in real time
  - decides to keep some events

    e.g. those with
    - 2 muons
    - e or μ + 1 displaced track
    - 2 displaced tracks
      (fully hadronic!)



- *Silicon Vertex Trigger* (SVT) – part of trigger system that finds displaced tracks and triggers on heavy hadrons

CDF data used in these analyses



~ 1.0 fb^{-1}, CP violation studies in displaced trigger data

1.3 fb^{-1}, tagged $B_s \to J/\psi\phi$

1.7 fb^{-1}, untagged $B_s \to J/\psi\phi$

1.6 fb^{-1}, CP asymmetry in semileptonic decays

Neutral B_s System

- Time evolution of B_s flavor eigenstates described by Schrodinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

- Diagonalize mass (M) and decay (Γ) matrices

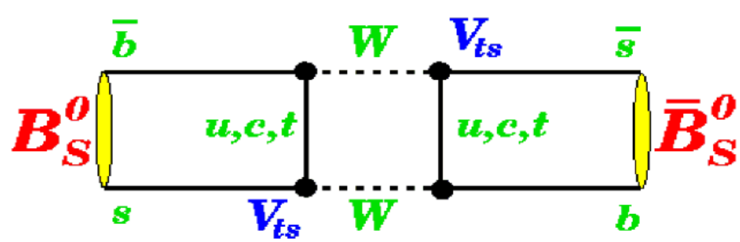
$\rightarrow$ mass eigenstates

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

where $q/p = \dfrac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}$

mass eigenvalues are different ($\Delta m_s = m_H - m_L \approx 2|M_{12}|$)

$\rightarrow$ B_s oscillates with frequency Δm_s



• Precisely measured by

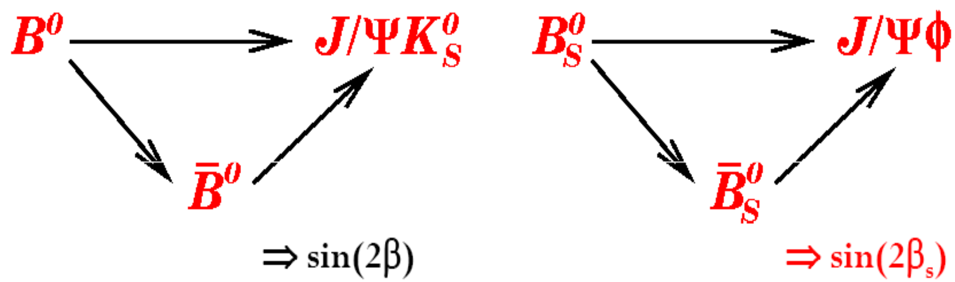
CDF	$\Delta m_s = 17.77 \pm 0.12\ \text{ps}^{-1}$
DØ	$\Delta m_s = 18.56 \pm 0.87\ \text{ps}^{-1}$

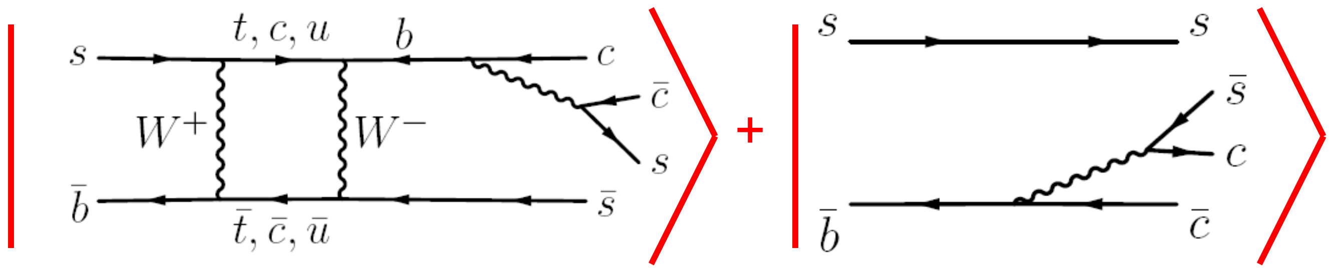
- Mass eigenstates have different decay widths

$\Delta\Gamma = \Gamma_L \quad \Gamma_H \approx 2|\Gamma_{12}|\cos(\Phi_s)$ where $\phi_S^{SM} = \arg\left(-\dfrac{M_{12}}{\Gamma_{12}}\right) \approx 4 \times 10^{-3}$

CP violation in $B_s \to J/\psi\phi$ decays

- Analogously to the neutral B^0 system, CP violation in B_s system occurs through interference of decay with and without mixing:





- β_s in SM is predicted to be very small: $\beta_s^{\mathrm{SM}} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$

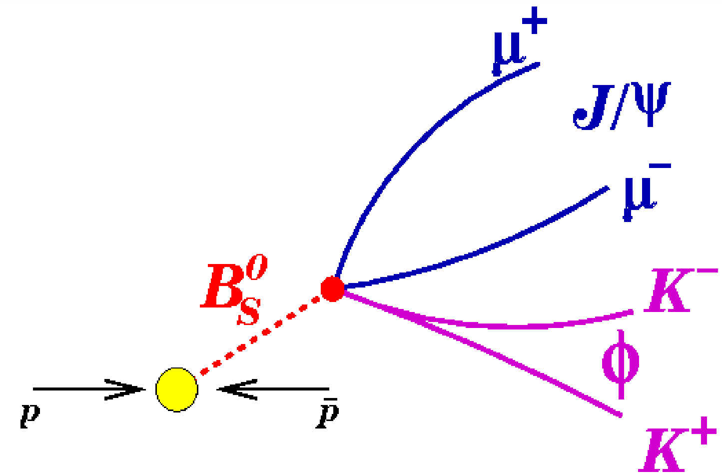
- New Physics affects the CP violation phase $2\beta_s = 2\beta_s^{\mathrm{SM}} - \phi_s^{\mathrm{NP}}$

- If NP phase ϕ_s^{NP} dominates → $2\beta_s = -\phi_s^{\mathrm{NP}}$

$B_s \rightarrow J/\psi\phi$ phenomenology

- Extremely rich physics

- Can measure lifetime, decay width, and, using known Δm_s, CP violating phase β_s



- B_s (spin 0) → J/ψ(spin 1) φ(spin 1) ==>
  3 different angular momentum final states:
  L = 0 (s-wave), L = 2 (d-wave) → CP even

  L = 1 (p-wave) → CP odd

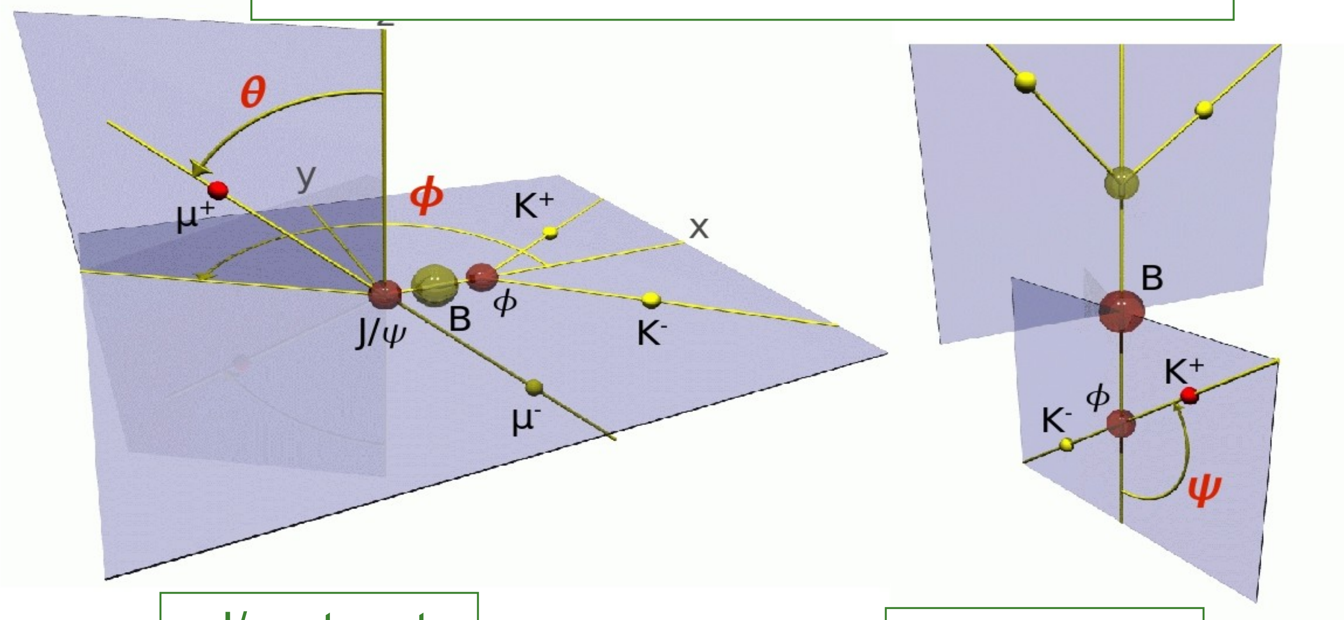
• Three angular momentum states form a basis for the final J/ψφ state

• Use alternative "transversity basis" in which the vector meson polarizations w.r.t. direction of motion are either:
  - **longitudinal (0)** → **CP even**
  - **transverse (‖ parallel to each other)** → **CP even**

  - **transverse (⊥ perpendicular to each other)** → **CP odd**

"Transversity" Basis

Two different reference frames



J/ψ at rest

Φ at rest

Decay amplitude decomposed (in terms of linear polarization) when J/ψ and ϕ are

- A_0: longitudinally polarized (CP-even)
- $A_{\|}$: transversely polarized and $\|$ to each other (CP-even)
- $A_{\perp}$: transversely polarized and $\perp$ to each other (CP-odd)

=> 3 angles describe directions of final decay products $\rightarrow \rho=\rho(\cos\theta,\phi,\cos\psi)$

"Strong" phases: $\delta_{\perp}$ = arg[$A_{\perp}$*A_0], $\delta_{\|}$ =arg[$A_{\|}$*A_0],

$B_s \to J/\psi\phi$ phenomenology

- Good approximation: $\phi_s \approx 0$
  ==> mass eigenstates $|B_s^L\rangle$ and $|B_s^H\rangle$ are CP eigenstates

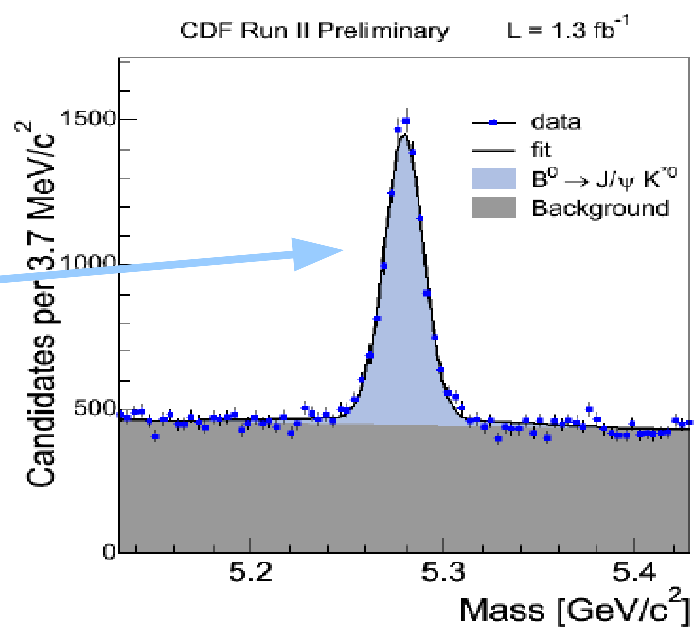
  → use angular information to separate heavy and light states
  → determine decay width difference

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

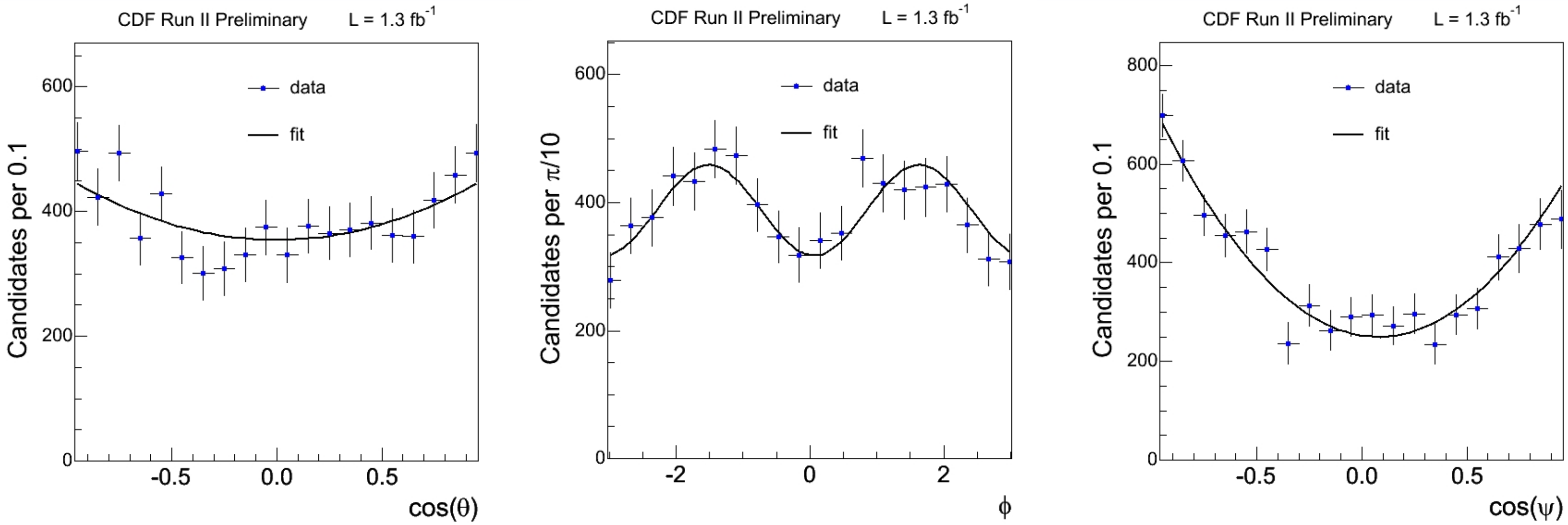
  → some sensitivity to CP violating phase β_s

- Determine B_s flavor at production (flavor tagging)
  → improve sensitivity to β_s

- Cross-check procedure for angular decomposition on $B^0 \to J/\psi K^{*0}$ (~7800 events from 1.3 fb^{-1})



Check amplitude decomposition on $B^0 \rightarrow J/\psi K^{*0}$



- In agreement *(and competitive with)* the latest BaBar and Belle result:
  e.g., BaBar: PRD 76,031102 (2007)

$$c\tau = 456 \pm 6\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$$

$$|A_0(0)|^2 = 0.569 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$$

$$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\text{stat}) \pm 0.006\ (\text{syst})$$

$$\delta_\parallel = -2.96 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$

$$\delta_\perp = \quad 2.97 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$$

$$|A_0(0)|^2 = 0.556 \pm 0.009\ (\text{stat}) \pm 0.010\ (\text{syst})$$

$$|A_\parallel(0)|^2 = 0.211 \pm 0.010\ (\text{stat}) \pm 0.006\ (\text{syst})$$

$$\delta_\parallel = -2.93 \pm 0.08\ (\text{stat}) \pm 0.04\ (\text{syst})$$

$$\delta_\perp = \quad 2.91 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$

Decay PDF for B^0_s and $\bar{B}^0_s$

B^0_s term

$$\frac{d^4P(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho})$$
$$+ |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_+ f_4(\vec{\rho})$$
$$+ |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_+ f_6(\vec{\rho}),$$

anti-B^0_s

$$\frac{d^4\overline{P}(t,\vec{\rho})}{dt\,d\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho})$$
$$+ |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_- f_4(\vec{\rho})$$
$$+ |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_- f_6(\vec{\rho}),$$

A_0, $A_\parallel$, $A_\perp$: transition amplitudes in a given polarization state at time 0

$f(\rho)$: angular distribution for a given polarization state

Time Evolution with Flavor Tagging

$$\mathcal{T}_\pm = e^{-\Gamma t} \quad \times \quad [\cosh(\Delta\Gamma t/2) \mp \boxed{\cos(2\beta_s)} \sinh(\Delta\Gamma t/2) \mp \eta \boxed{\sin(2\beta_s)} \sin(\boxed{\Delta m_s} t)] \,,$$

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \quad \times \quad [\sin(\delta_\perp - \delta_\parallel) \cos(\boxed{\Delta m_s} t) - \cos(\delta_\perp - \delta_\parallel) \boxed{\cos(2\beta_s)} \sin(\boxed{\Delta m_s} t) \pm \cos(\delta_\perp - \delta_\parallel) \boxed{\sin(2\beta_s)} \sinh(\Delta\Gamma t/2)] \,,$$

$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \quad \times \quad [\sin(\delta_\perp) \cos(\boxed{\Delta m_s} t) - \cos(\delta_\perp) \boxed{\cos(2\beta_s)} \sin(\boxed{\Delta m_s} t) \pm \cos(\delta_\perp) \boxed{\sin(2\beta_s)} \sinh(\Delta\Gamma t/2)] \,.$$

β_s sensitivity

CDF result as input

Step #1: "untagged" $B_s \to J/\psi\phi$ analysis

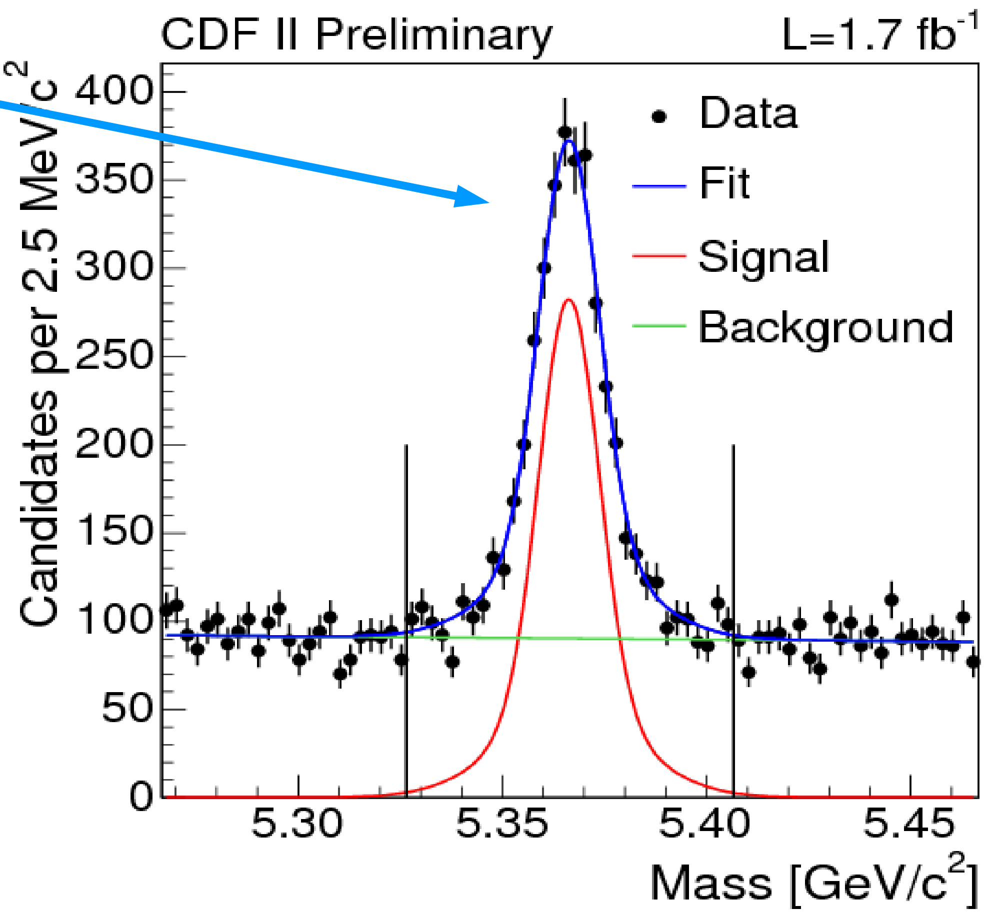
- "Untagged" = No flavor tagging information
- Sum up B^0_s and anti-B^0_s PDF equally
- Many terms cancel

$$
\begin{aligned}
\mathcal{T}_\pm = e^{-\Gamma t} \quad \times \quad & \left[\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)\right. \\
& \left.\cancel{\mp\ \eta \sin(2\beta_s)\sin(\Delta m_s t)}\right], \\
\mathcal{U}_\pm = \pm e^{-\Gamma t} \quad \times \quad & \left[\cancel{\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)}\right. \\
& - \cancel{\cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)}\sin(\Delta m_s t) \\
& \left.\pm\ \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right], \\
\mathcal{V}_\pm = \pm e^{-\Gamma t} \quad \times \quad & \left[\cancel{\sin(\delta_\perp)\cos(\Delta m_s t)}\right. \\
& - \cancel{\cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t)} \\
& \left.\pm\ \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right].
\end{aligned}
$$

- Suited for precise measurement of $\Delta\Gamma$ and τ
- Still sensitive to β_s

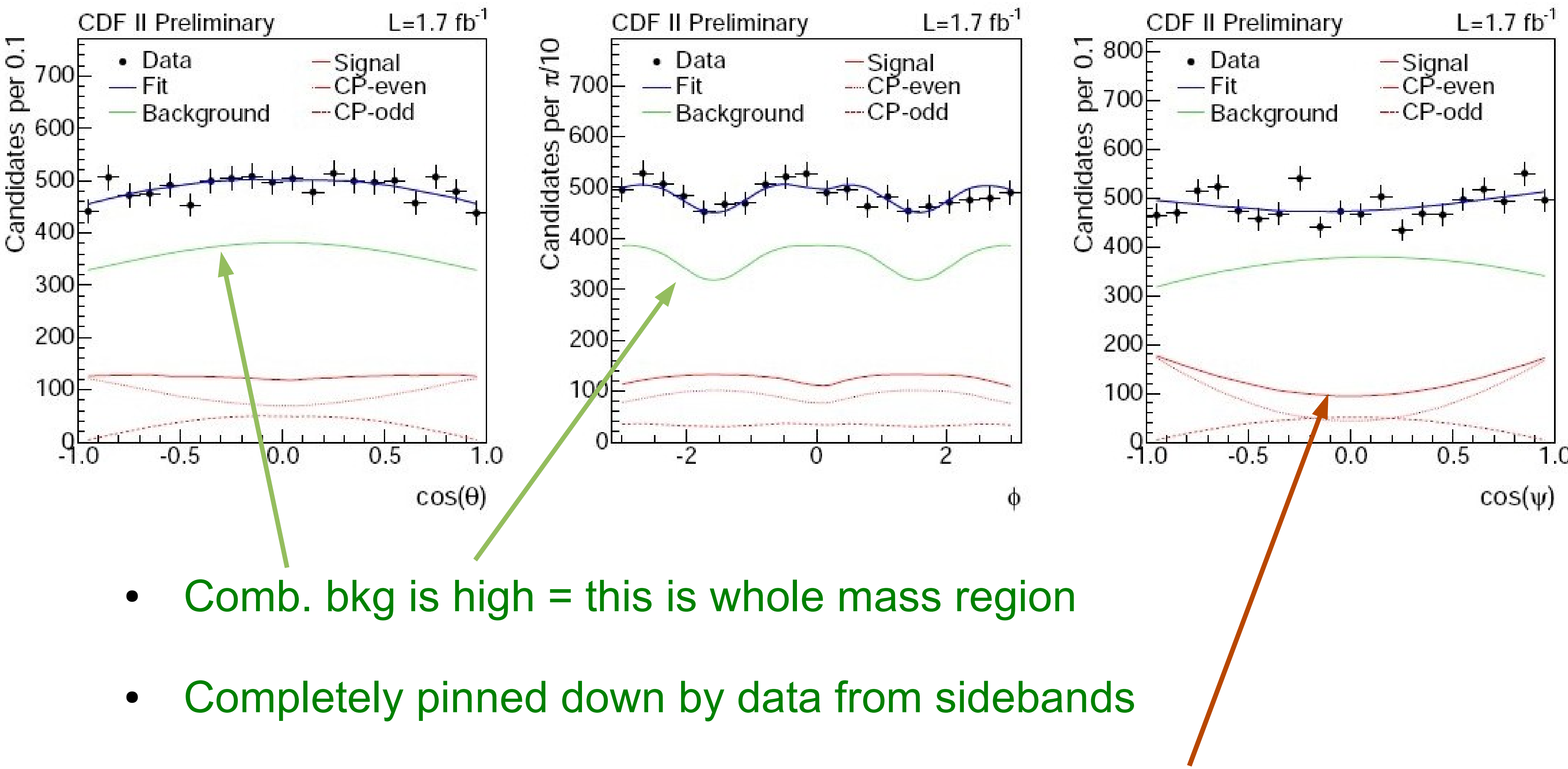
$B_s \rightarrow J/\psi\phi$ sample for untagged analysis

- ~ 2500 signal events in 1.7 fb-1
- Assume no CP violation ($i.e.$ $\beta_s = 0$)
- Most precise measurement of the B_s lifetime to date
- Confirms $\tau_s \sim \tau_d$



$\tau_s = 1.52$ +/- 0.04 (stat) +/- 0.02 (syst) ps

$B_s \rightarrow J/\psi\phi$ untagged: angle projections



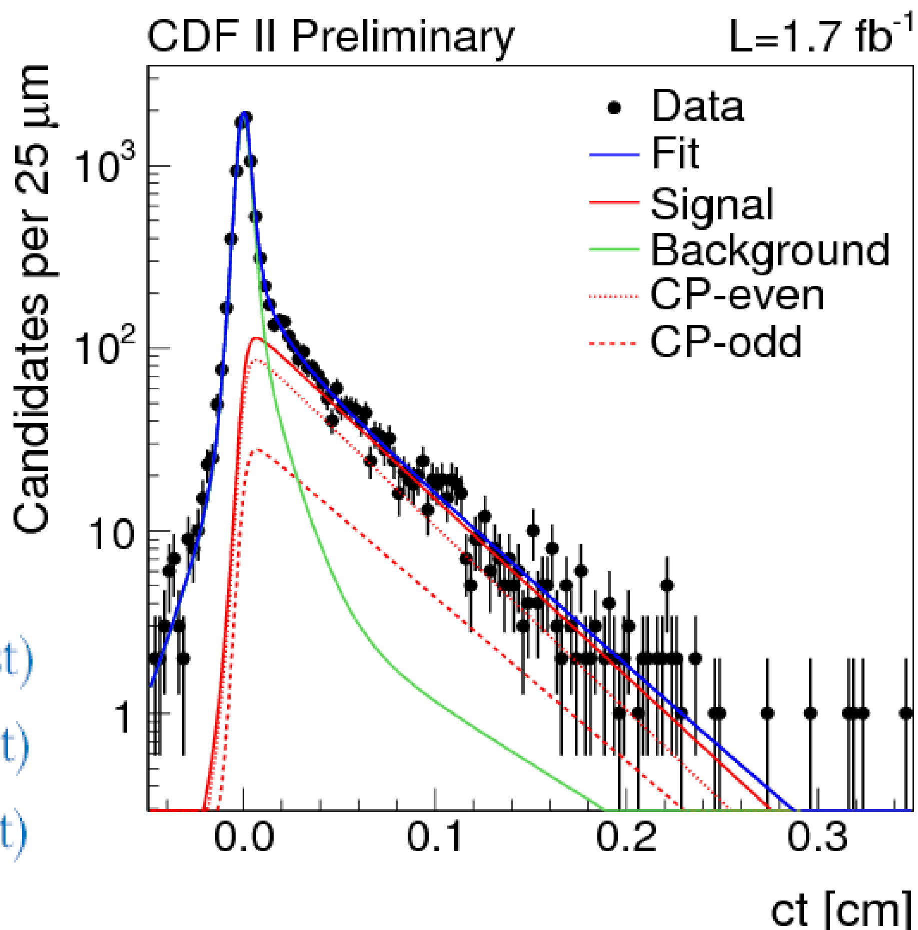
- Comb. bkg is high = this is whole mass region
- Completely pinned down by data from sidebands
- (Sideband-subtracted data agree well with signal PDF)

$\Delta\Gamma_s$ (B_s decay width)

- CP-even ($\approx B_s^{light}$) and CP-odd ($\approx B_s^{heavy}$) components have different lifetimes $\rightarrow \Delta\Gamma \neq 0$

- In agreement and 30-50% better than previous best measurements (DØ, 2007) and 2x better than PDG

$$|A_0(0)|^2 = 0.531 \pm 0.020\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$|A_\parallel(0)|^2 = 0.230 \pm 0.026\,(\text{stat}) \pm 0.009\,(\text{syst})$$
$$|A_\perp(0)|^2 = 0.239 \pm 0.029\,(\text{stat}) \pm 0.011\,(\text{syst})$$



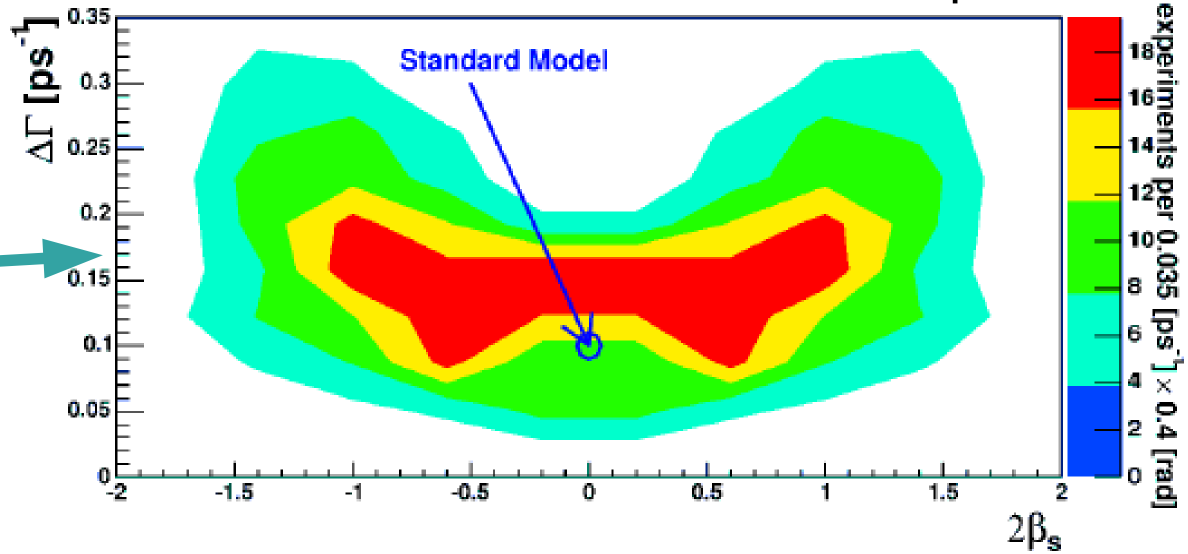
$$\boxed{\Delta\Gamma = 0.08 \text{ +/- } 0.06\ (\text{stat}) \text{ +/- } 0.01\ (\text{syst})\ \text{ps}^{-1}}$$

$B_s \to J/\psi\phi$ untagged: floating β_s

Even without tagging, have some sensitivity to β_s

But, there are biases seen in pseudo experiments

fits on simulated samples



Reasons:

- Loss of degrees of freedom: *e.g.* when $\Delta\Gamma \to 0$, $\delta_\perp$ is undetermined, no sensitivity to β_s at all: $\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$

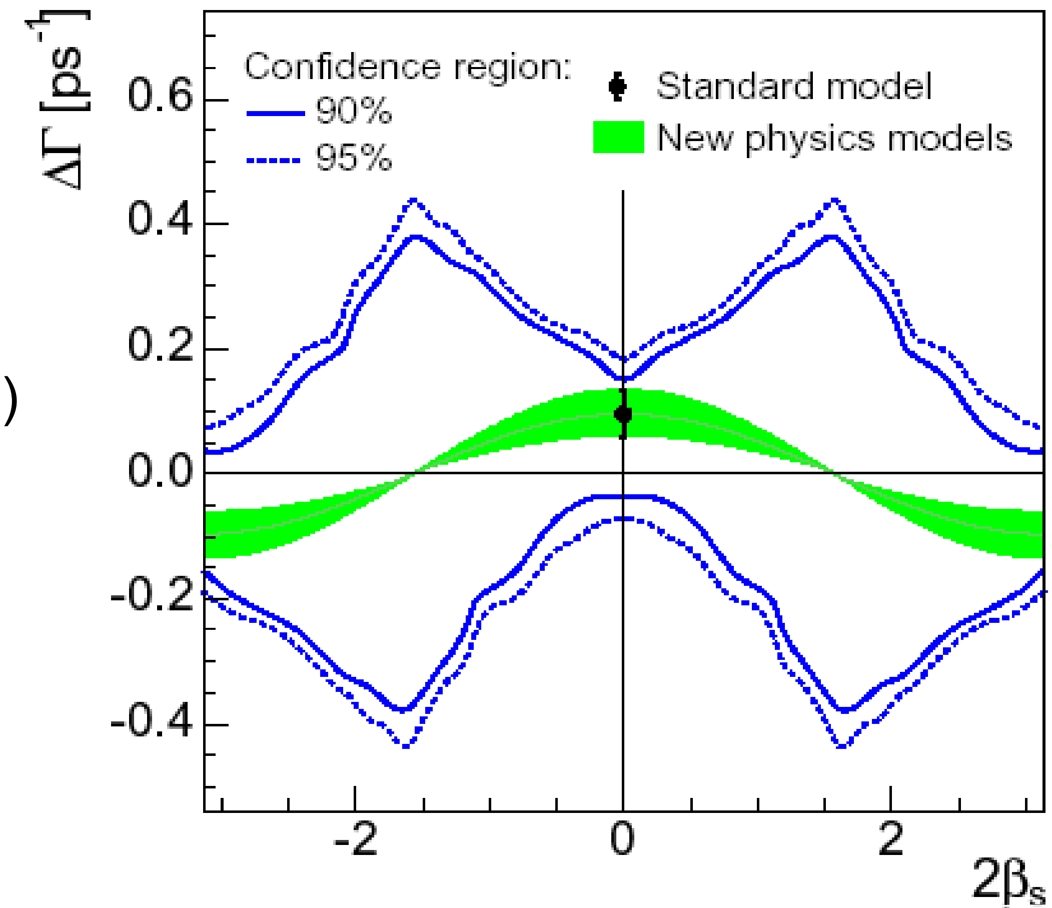
- *4-fold ambiguity existed in likelihood function (=> there are 4 equivallent minima!)*

$$2\beta_s \to -2\beta_s,\ \delta_\perp \to \delta_\perp + \pi$$

$$\Delta\Gamma \to -\Delta\Gamma,\ 2\beta_s \to 2\beta_s + \pi$$

Confidence Region without tagging

Use Likelihood-Ratio ordering (Feldman-Cousins) to determine Confidence Region in β_s – $\Delta\Gamma$ space.



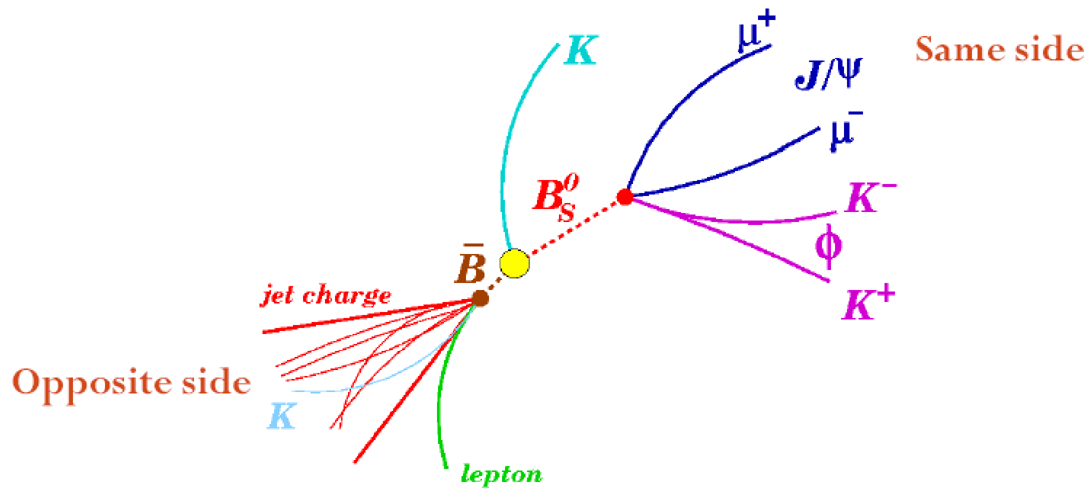
Under assumption of SM, the probability of data fluctuating to our observation or better is 22% or 1.2σ.

Step #2: add flavor tagging

- Flavor tagging produces
  - tag decision
  - this tag's *predicted* dilution (*i.e.* = 1-2w)

- Opposite Side Tagging (OST) calibrated on B^+

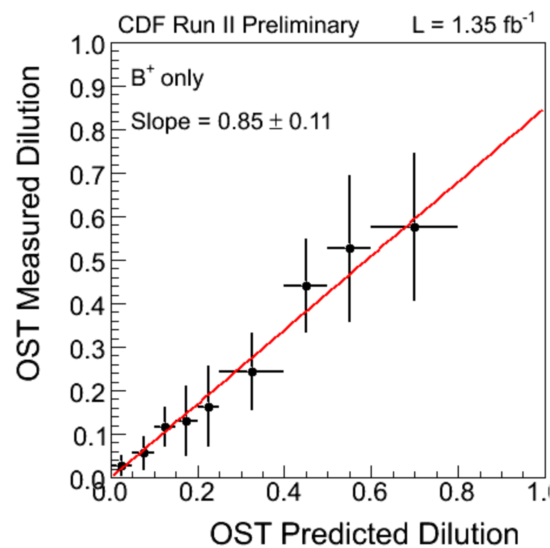
- Same Side (Kaon) Tagging calibrated on MC (but checked on mixing measurement)

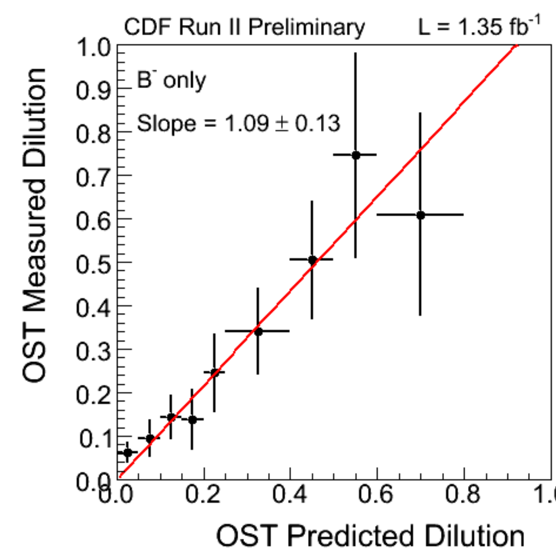


OST efficiency 96 +/- 1%
OST dilution: 11 +/- 2%

SST efficiency 50 +/- 1%
SST dilution 27 +/- 4%

Total $\varepsilon D^2 \sim 4.5\%$

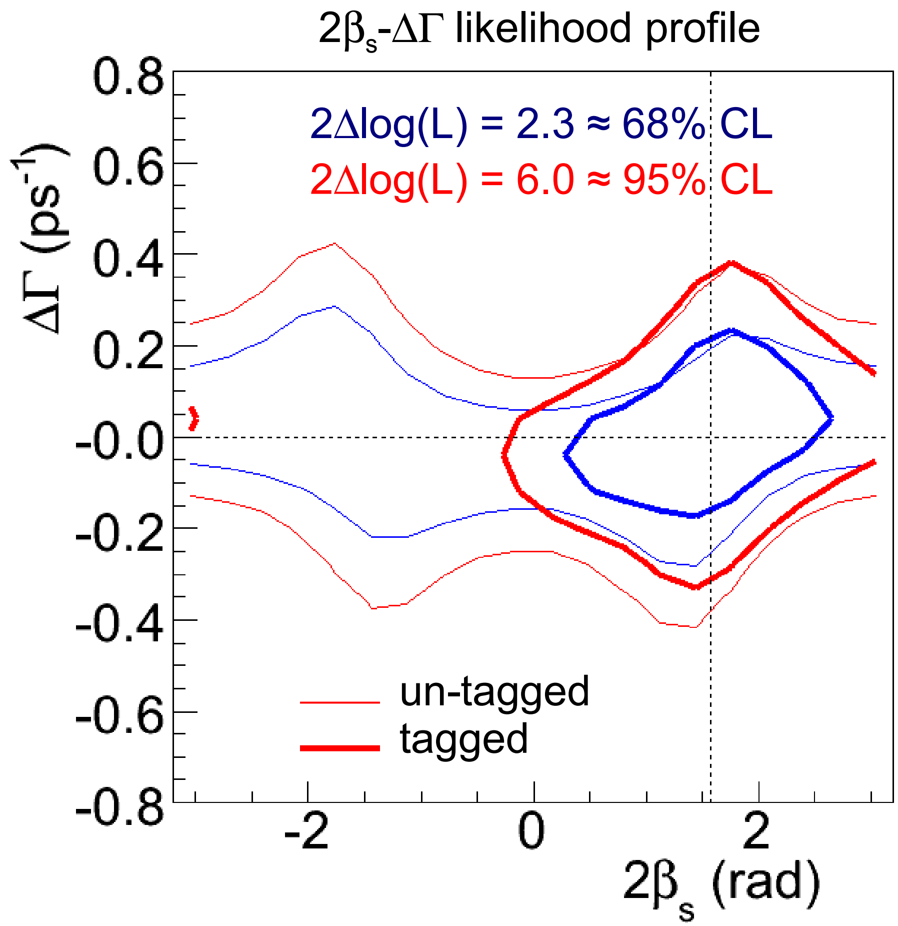




Study effect of tagging in Toy MC

- PDF predicts better sensitivity to β_s but still with 2 minima due to symmetry:

$$2\beta_s \to \pi - 2\beta_s$$
$$\Delta\Gamma \to -\Delta\Gamma$$
$$\delta_\parallel \to 2\pi - \delta_\parallel$$
$$\delta_\perp \to \pi - \delta_\perp$$



- Improvement of parameter resolution is small due to limited tagging power (εD^2 ~ 4.5% vs ~30% at BaBar/Belle)

- However:

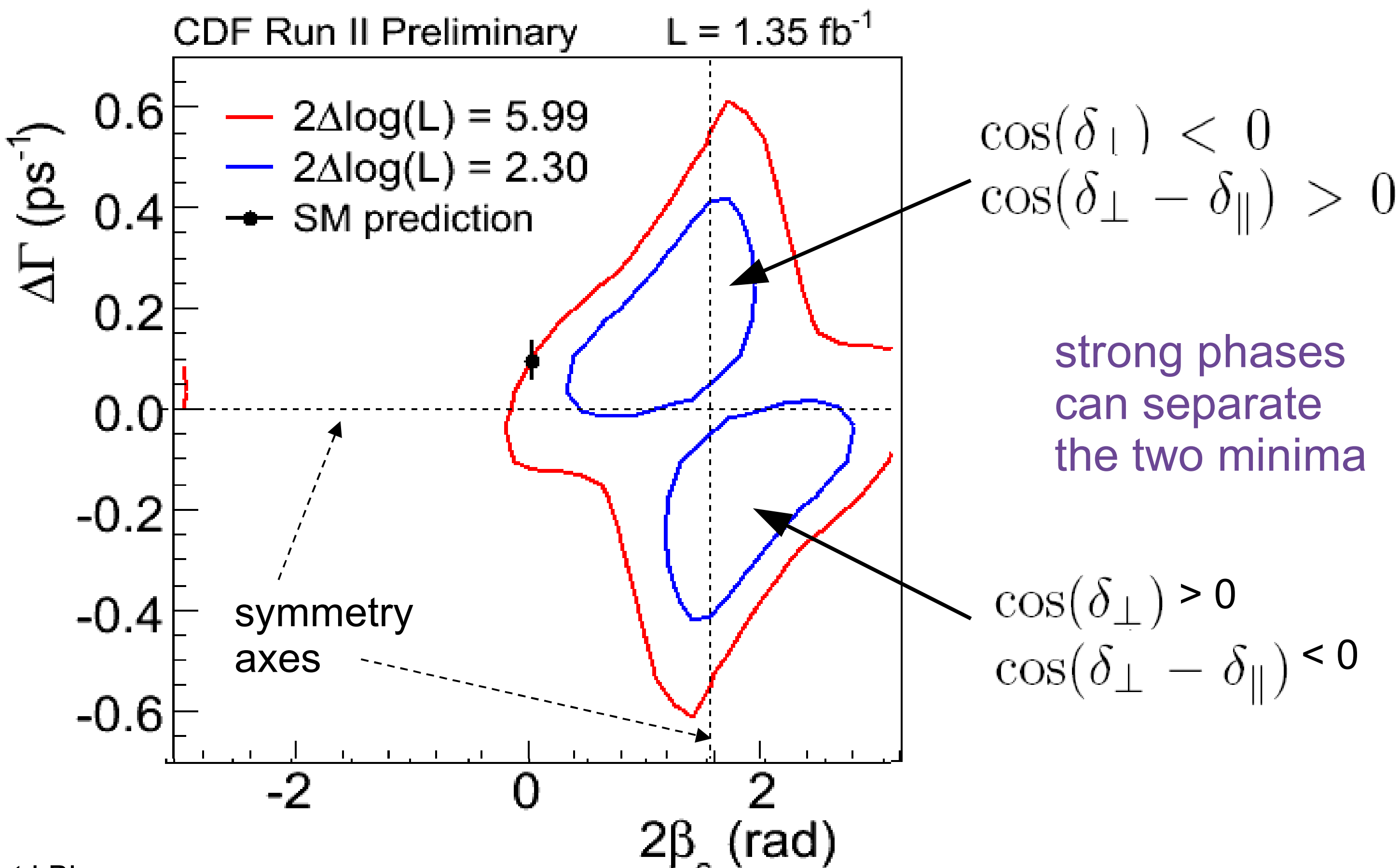
  $\beta_s \to -\beta_s$ no longer a symmetry

  $\to$ 4-fold ambiguity reduced to 2-fold ambiguity

  $\to$ ***allowed region for β_s is reduced to half!***

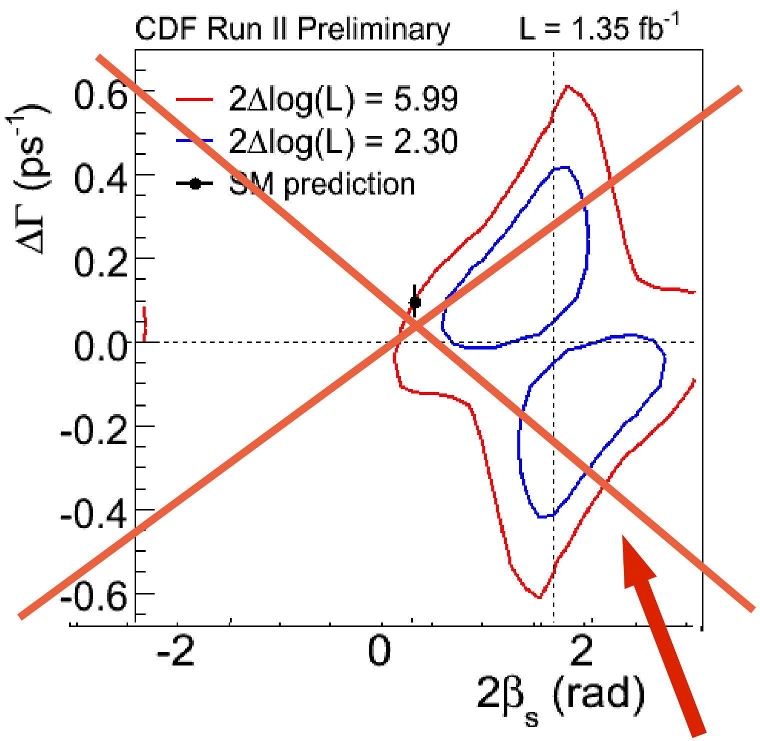
Tagged $B_s \to J/\psi\phi$ analysis

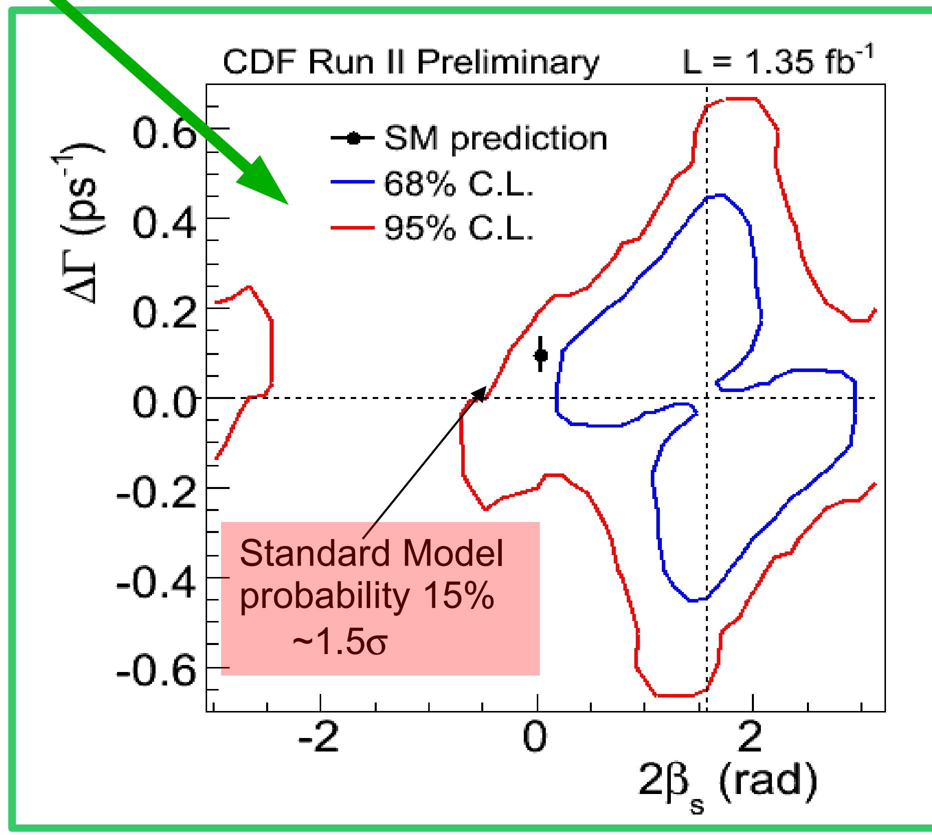
- First tagged analysis of $B_s \to J/\Psi\Phi$ (1.4 fb^{-1})
- Signal B_s yield ~2000 events with S/B ~ 1



Tagged $B_s \to J/\psi\phi$ analysis

- As in untagged: irregular likelihood doesn't allow quoting point estimate
- Quote Feldman-Cousins confidence regions ***(including systematics!)***



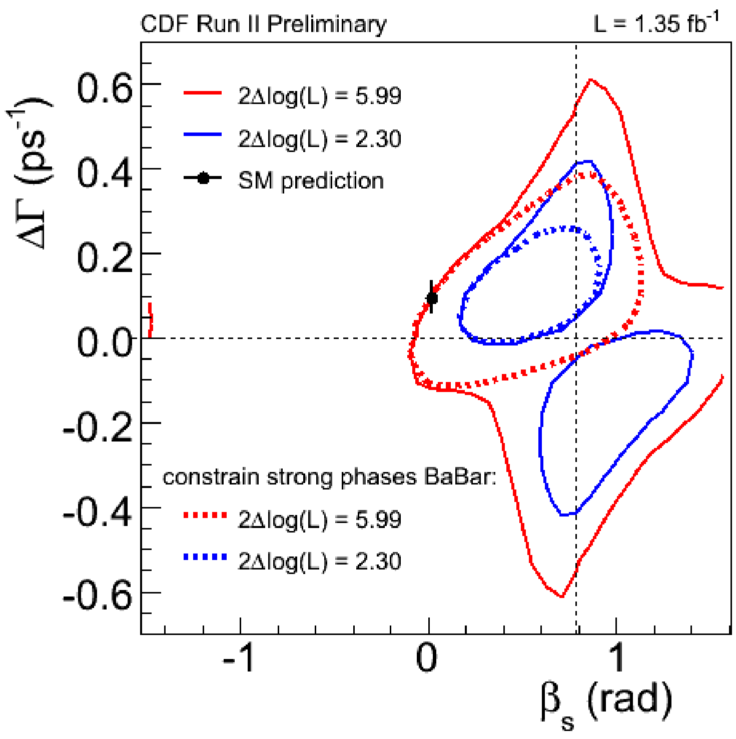


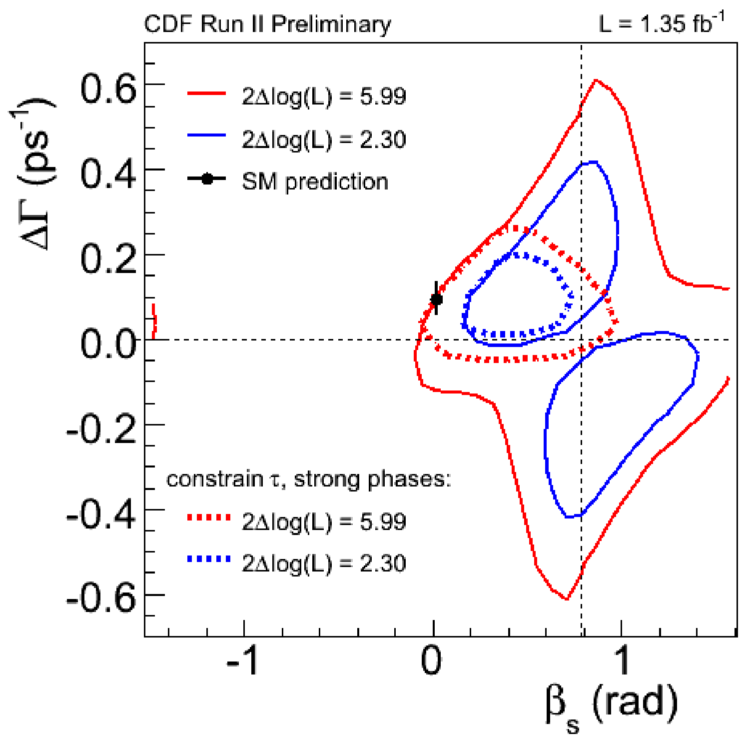
- Confidence regions are _underestimated_ when using $2\Delta\log L = 2.3$ (6.0) to approximate 68% (95%) C.L. regions

β_s with external constraints

- Spectator model: B_s and B^0 have similar lifetimes and strong phases
- Likelihood profiles with external constraints from *B* factories:

constrain strong phases to B^0: | constrain lifetime and strong phases:

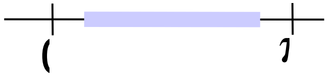




- External constraints on strong phases remove residual 2-fold ambiguity

β_s: 1-Dimensional Feldman-Cousins results

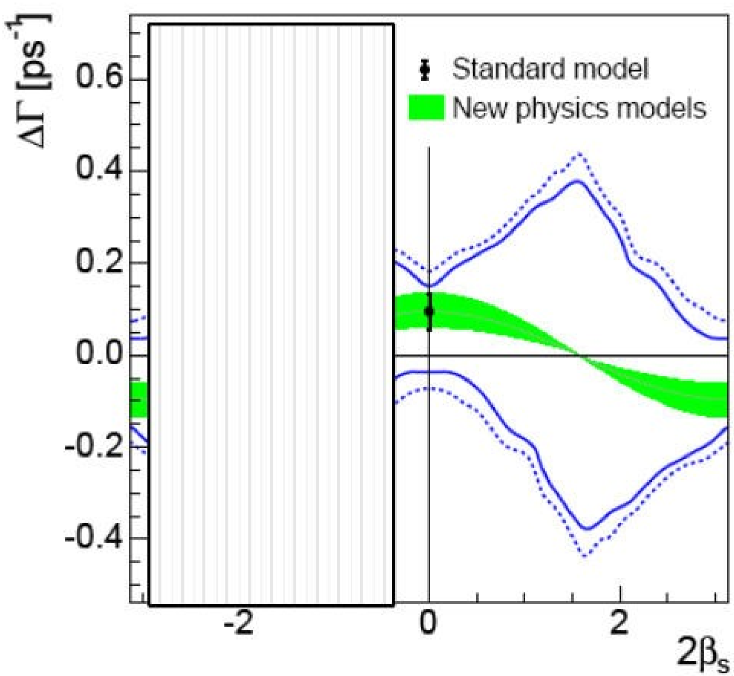
- 1D Feldman-Cousins procedure without external constraints:
  $2\beta_s$ in [0.32, 2.82] at the 68% C.L.

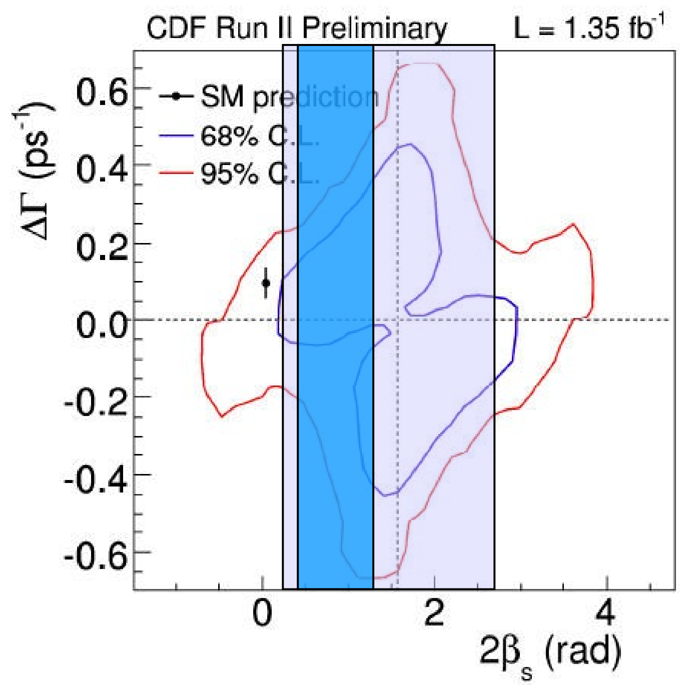


$2\beta_s$

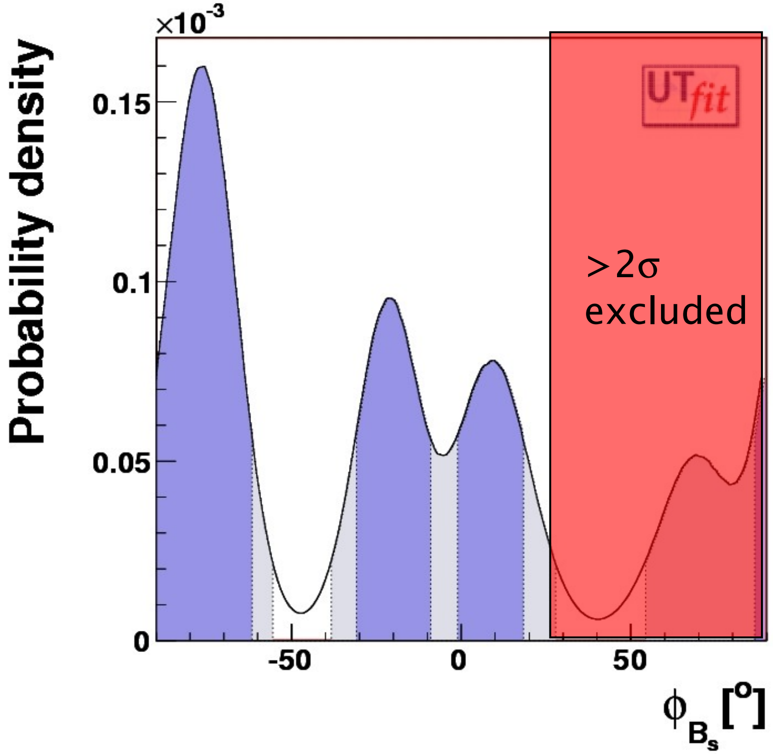
- 1D Feldman-Cousins with external constraints on strong phases, lifetime and $|\Gamma_{12}| = 0.048 +/- 0.018\ ps^{-1}$:
  $2\beta_s$ in [0.40, 1.20] at 68% C.L.

$2\beta_s$

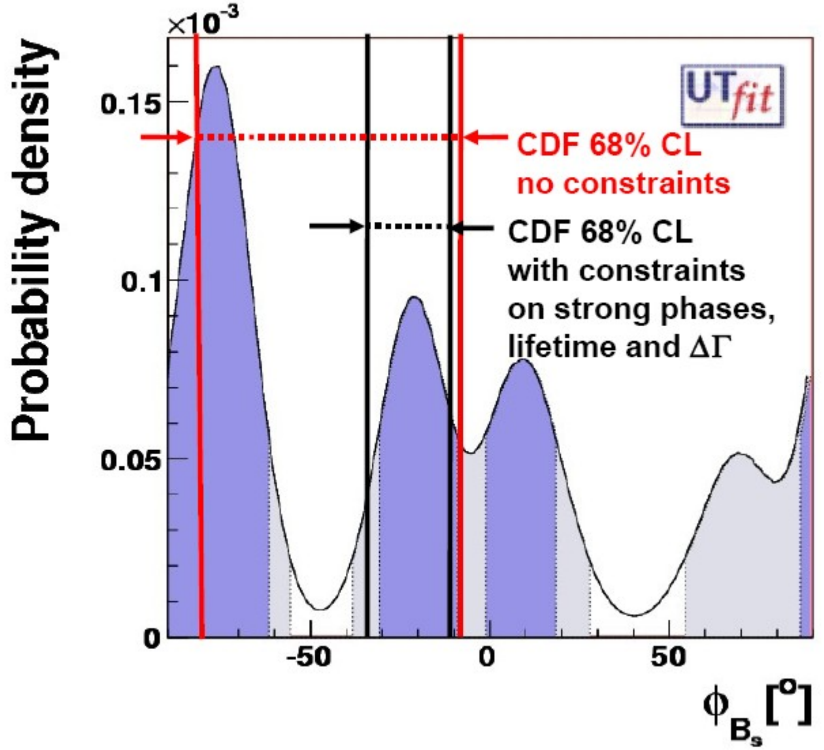




Impact of the tagged β_s analysis



2D result from Feldman-Cousins



1D result from Feldman Cousins

CP asymmetry in semileptonic Bs decays

- Alternative approach to ϕ_s (β_s): an *inclusive* measurement
- Semileptonic CP asymmetry related to $\phi_s^{SM} = \arg(-M_{12}/\Gamma_{12})$

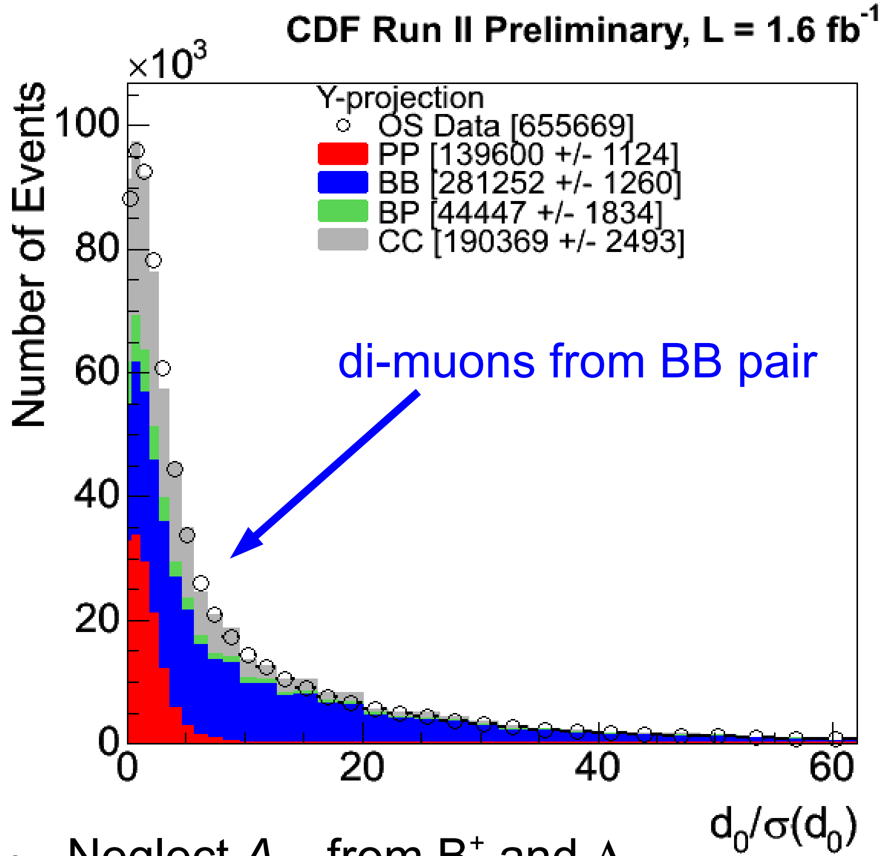
$$A_{SL}^{s,unt} = \frac{1}{2}\frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

- It could be combined with $2\beta_s$-$\Delta\Gamma$ measurement from $B_s \to J/\psi\phi$ but CDF hasn't done so yet.
- We measure it by counting the number of ++ and – – muon pairs:

$$A_{corr} = \frac{N_{obs}^{++}(\frac{1}{\epsilon_+^2}) - N_{obs}^{--}(\frac{1}{\epsilon_-^2})}{N_{obs}^{++}(\frac{1}{\epsilon_+^2}) + N_{obs}^{--}(\frac{1}{\epsilon_-^2})} = \frac{N_{obs}^{++} - N_{obs}^{--}(\frac{\epsilon_+}{\epsilon_-})^2}{N_{obs}^{++} + N_{obs}^{--}(\frac{\epsilon_+}{\epsilon_-})^2}$$

CP asymmetry in semileptonic B_s decays

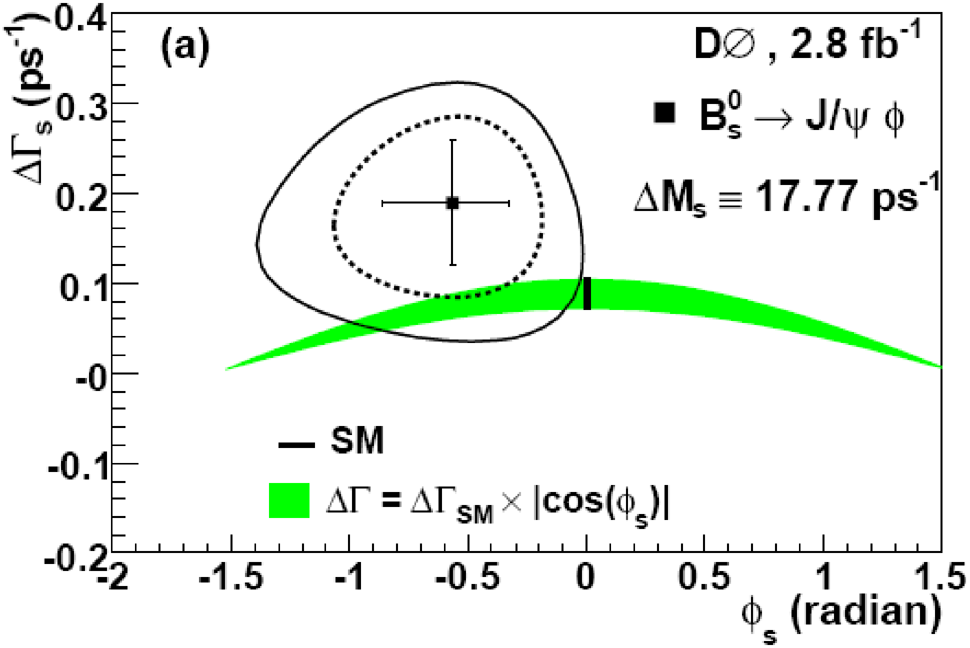
- dedicated di-μ trigger (high mass)
  - 660k opposite sign
  - 440k same sign dimuon pairs
- use d_0 of two muons to separate
  - di-μ from BB pair
  - charm (CC)
  - prompt (PP)
  - B+prompt (BP)
- correct for
  - hadrons faking muons
  - detector and trigger asymmetries



- Neglect A_{CP} from B^+ and Λ_b
- Correct for A^d_{SL} from B factories:

$$\boxed{A^s_{SL} = 0.020 \pm 0.021(stat) \pm 0.016(syst) \pm 0.009(inputs)}$$

D0 result and new UTfit preprint



$\phi_s = -0.57^{+0.24}_{-0.30}(\text{stat})\ ^{+0.07}_{-0.02}(\text{syst})$

$\Delta\Gamma = +0.19 \pm 0.07(\text{stat})\ ^{+0.02}_{-0.01}(\text{syst})\ ps^{-1}$

With constraint from HFAG:
$\delta 1 = -0.46,\ \delta 2 = 2.92$
Constraint within $\pi/5$

From UTfit 3σ ???:

arXiv.org > hep-ph > arXiv:0803.0659v1

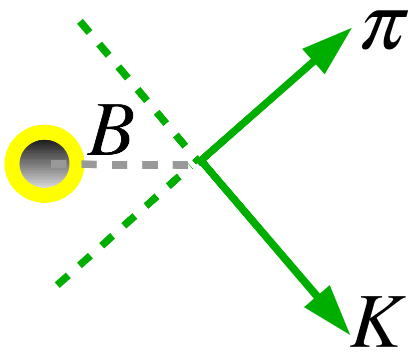
FIRST EVIDENCE OF NEW PHYSICS IN $b \leftrightarrow s$ TRANSITIONS

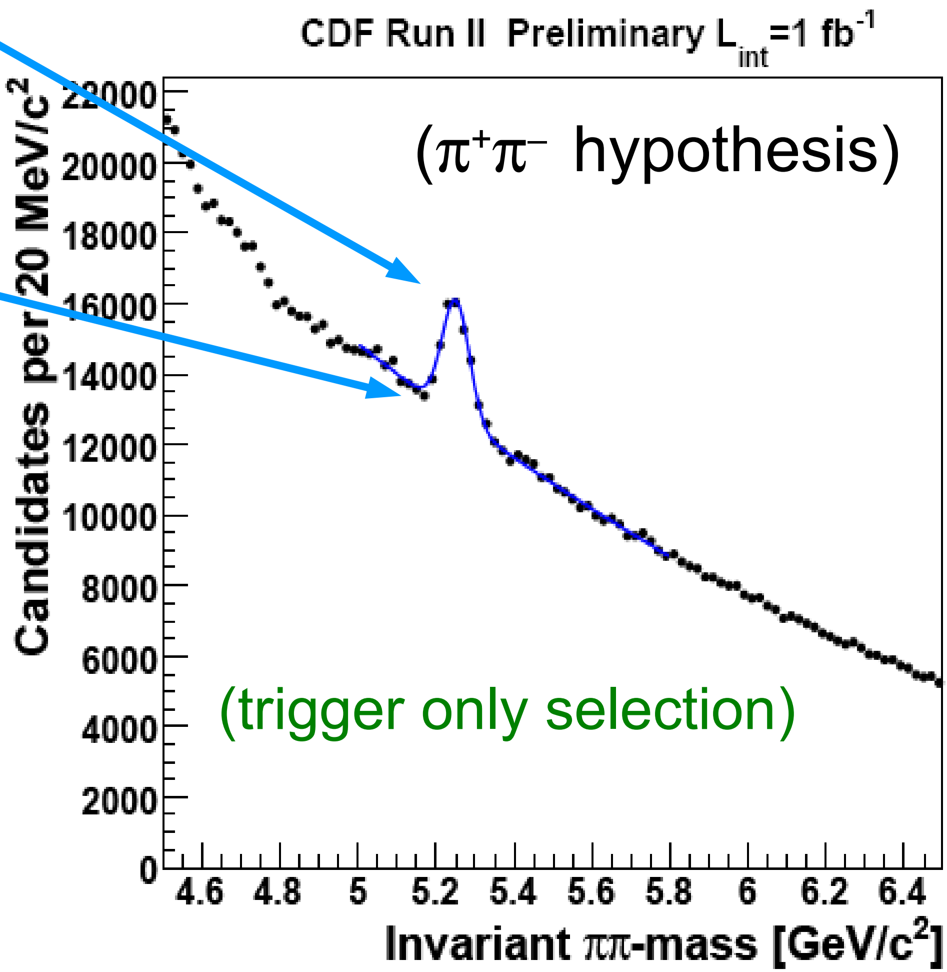
(UT*fit* Collaboration)

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than $\boxed{3\sigma}$ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

Composition of $B \to h^+ h'^-$

- Bump a mixture of: $B_d \to K\pi$
  $B_d \to \pi\pi$
  $B_s \to KK$
  $B_s \to K\pi$





- Need to optimize & disentangle
- Using dE/dx
  - Effective K/π separation of dE/dx ~ 1.4 σ

⟹ Separate contributions on a statistical basis

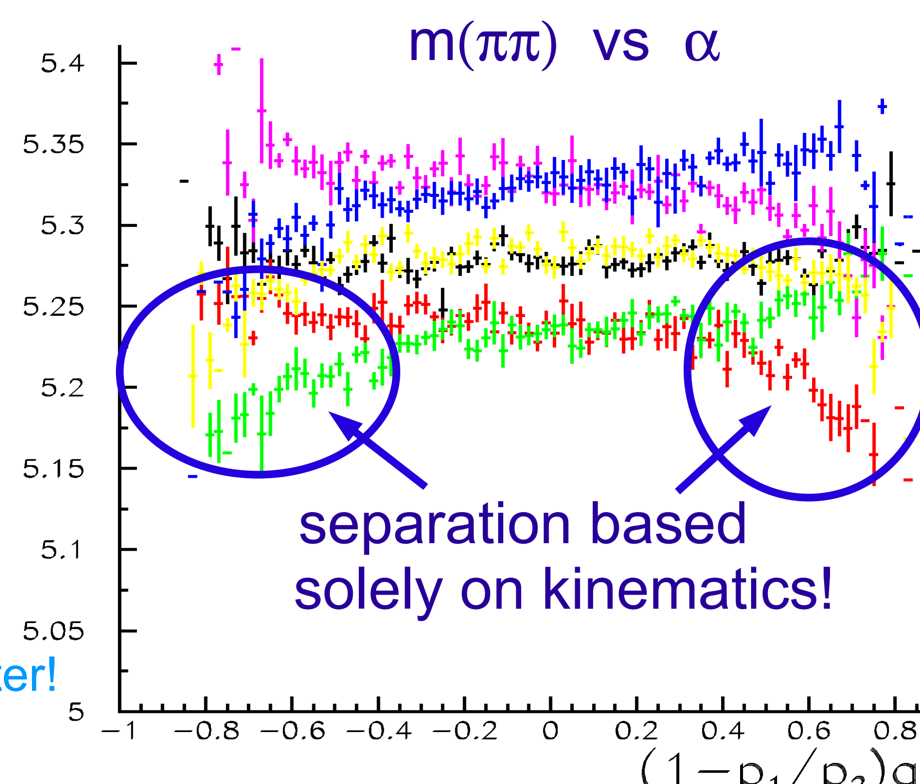
Tools to decompose $B \to h^+ h'^-$

- Multi-dimensional unbinned likelihood fit
- m(ππ) + a quantity related to dE/dx
- Kinematics for two other dimensions:
  - $p_{tot} = p_1 + p_2$
  - Momentum imbalance α (assuming $p_1 < p_2$)

$$\alpha = \left(1 - \frac{p_1}{p_2}\right) \cdot q_1$$

Mixes charge and kinematics

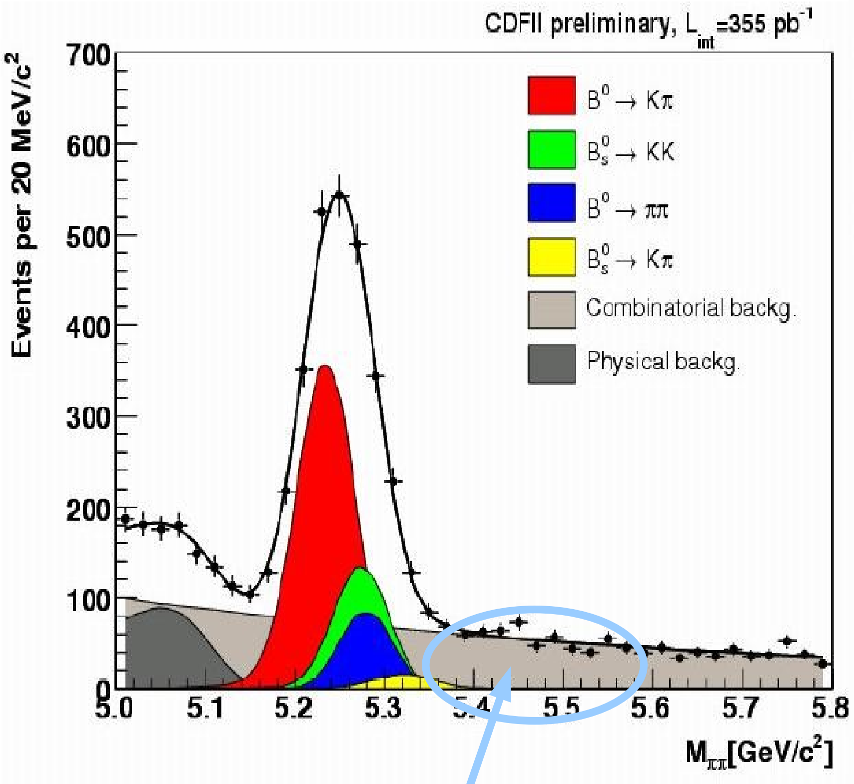
==> Can separate matter from antimatter!

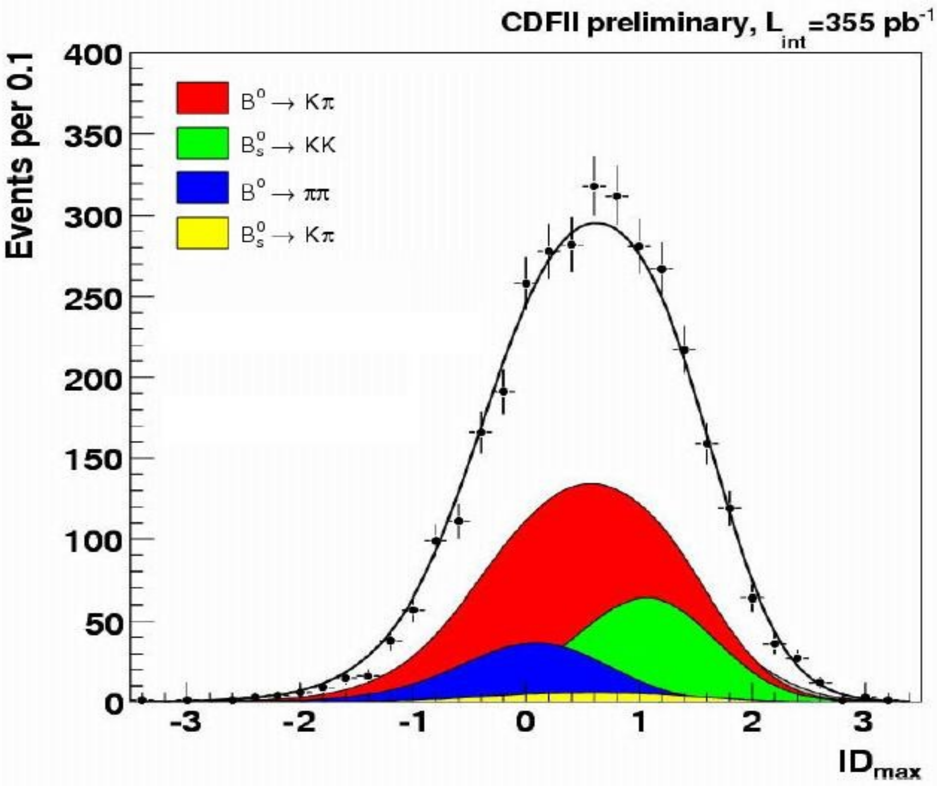


$B \to h^+h'^-$: old projections (as example)

- Can clearly separate these decay modes

  (But, these are ***old*** plots, story gets more complicated)

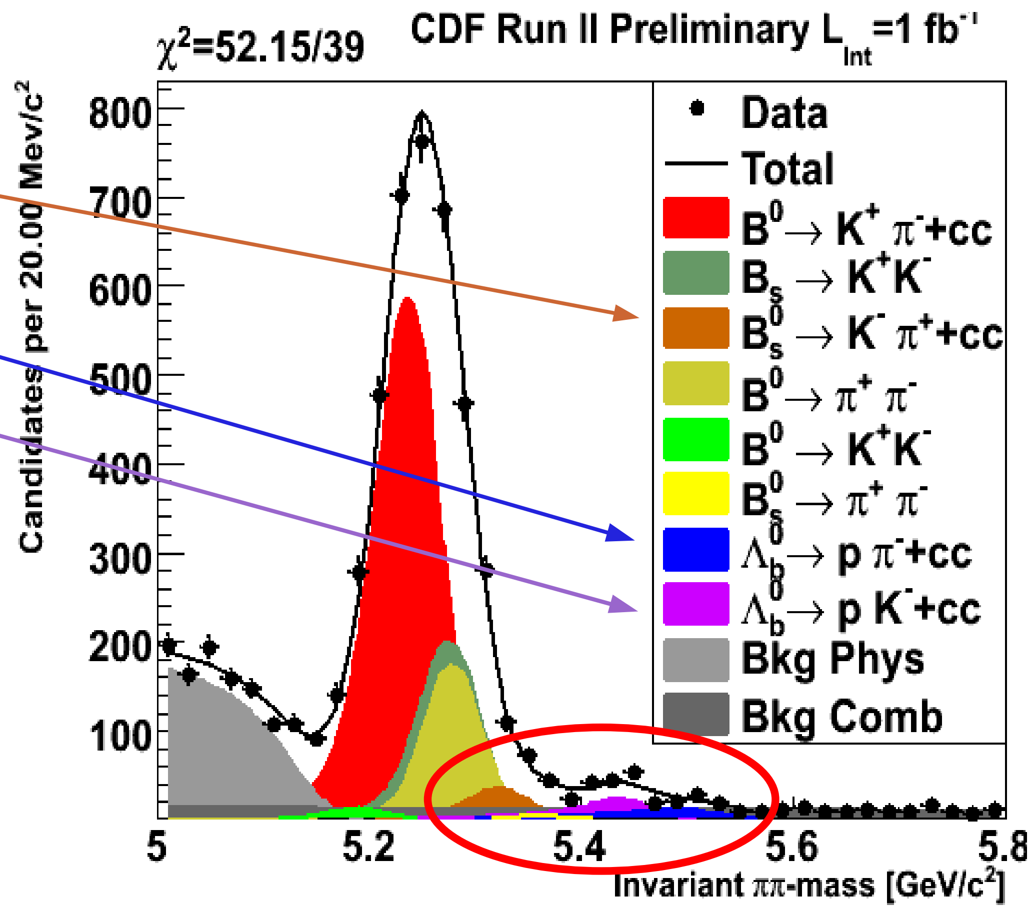




- A stubborn bump that doesn't go away when we blind the signal region and optimize using sidebands... ???

$B \to h^+h'^-$: modern approach

- Solution: also include $\Lambda_b \to p\pi$ and $\Lambda_b \to pK$ in the fit!
- Optimize twice:
  - once for $B_s \to K\pi$
  - separately for $\Lambda_b \to p\pi$ and $\Lambda_b \to pK$



- Fit result: first observation of all three channels!
- Moral: no safe place to hide from the signal!
(Just like SUSY @ LHC.)

BR's and Acp in $B_{s(d)} \rightarrow K^-\pi^+$ (in 1 fb^{-1})

- $B_s \rightarrow K^-\pi^+$ mode can be used for measuring γ
- A_{CP} in $B_s \rightarrow K^-\pi^+$ could provide a powerful model-independent test of the source of direct CP asymmetry observed in $B^0 \rightarrow K^-\pi^+$
- We see a > 2σ effect:

$$\boxed{A_{\mathrm{CP}} = \frac{N(\overline{B}^0_s \rightarrow K^+\pi^-) - N(B^0_s \rightarrow K^-\pi^+)}{N(\overline{B}^0_s \rightarrow K^+\pi^-) + N(B^0_s \rightarrow K^-\pi^+)} = 0.39 \pm 0.15\ (stat.) \pm 0.08\ (syst.)}$$

- CP asymmetry in $B^0 \rightarrow K^-\pi^+$ (improves world average from 6σ to 7σ; and this is only 1/3 of the data...)

$$A_{\mathrm{CP}} = \frac{N(\overline{B}^0 \rightarrow K^-\pi^+) - N(B^0 \rightarrow K^+\pi^-)}{N(\overline{B}^0 \rightarrow K^-\pi^+) + N(B^0 \rightarrow K^+\pi^-)} = -0.086 \pm 0.023\ (stat.) \pm 0.009\ (syst.)$$

BR's and Acp in $\Lambda_b \to p\,\pi(K)$ (in 1 fb^{-1})

- Results:

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = \frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-) - \mathcal{B}(\overline{\Lambda}_b^0 \to \overline{p}\pi^+)}{\mathcal{B}(\Lambda_b^0 \to p\pi^-) + \mathcal{B}(\overline{\Lambda}_b^0 \to \overline{p}\pi^+)} = 0.03 \pm 0.17\,(stat.) \pm 0.05\,(syst.)$$

$$A_{CP}(\Lambda_b^0 \to pK^-) = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-) - \mathcal{B}(\overline{\Lambda}_b^0 \to \overline{p}K^+)}{\mathcal{B}(\Lambda_b^0 \to pK^-) + \mathcal{B}(\overline{\Lambda}_b^0 \to \overline{p}K^+)} = 0.37 \pm 0.17\,(stat.) \pm 0.03\,(syst.)$$

- First CP asymmetry meas. in b-baryon decays (expect SM ~ 10%)

- Additionally, first measurement of branching fraction relative to $B^0 \to K\pi$ decays:

$$\frac{\sigma(p\bar{p} \to \Lambda_b^0 X, p_T > 6\ \mathrm{GeV}/c)}{\sigma(p\bar{p} \to B^0 X, p_T > 6\ \mathrm{GeV}/c)} \frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.0415 \pm 0.0074\,(stat.) \pm 0.0058\,(syst.)$$

$$\frac{\sigma(p\bar{p} \to \Lambda_b^0 X, p_T > 6\ \mathrm{GeV}/c)}{\sigma(p\bar{p} \to B^0 X, p_T > 6\ \mathrm{GeV}/c)} \frac{\mathcal{B}(\Lambda_b^0 \to pK^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.0663 \pm 0.0089\,(stat.) \pm 0.0084\,(syst.)$$

BR's and Acp in $B^+ \to D^0 K^+$

- Measures quantities relevant for determination of the CKM angle γ

$arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ by measuring A^+_{CP}, A^-_{CP}, R^+_{CP} and R^-_{CP}

$$A_{CP+} = \frac{BR(B^- \to D^0_{CP+}K^-) - BR(B^+ \to D^0_{CP+}K^+)}{BR(B^- \to D^0_{CP+}K^-) + BR(B^+ \to D^0_{CP+}K^+)}$$

$$R_{CP+} = \frac{R_+}{R}$$ where:

$$R = \frac{BR(B^- \to D^0K^-) + BR(B^+ \to \overline{D}^0K^+)}{BR(B^- \to D^0\pi^-) + BR(B^+ \to \overline{D}^0\pi^+)}$$

$$R_+ = \frac{BR(B^- \to D^0_{CP+}K^-) + BR(B^+ \to D^0_{CP+}K^+)}{BR(B^- \to D^0_{CP+}\pi^-) + BR(B^+ \to D^0_{CP+}\pi^+)}$$

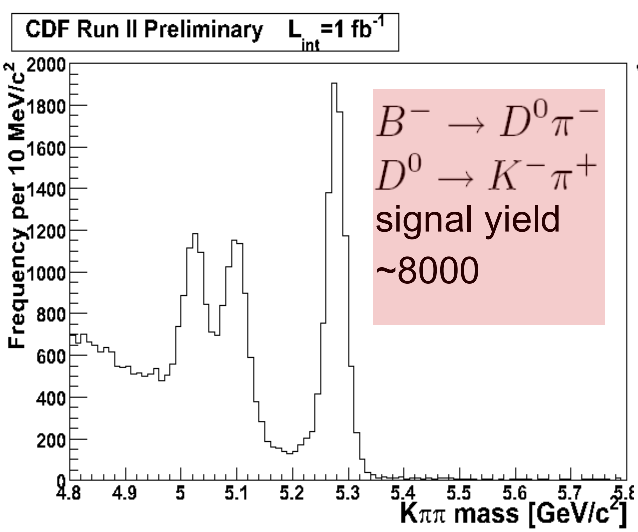
CP even eigenstate:

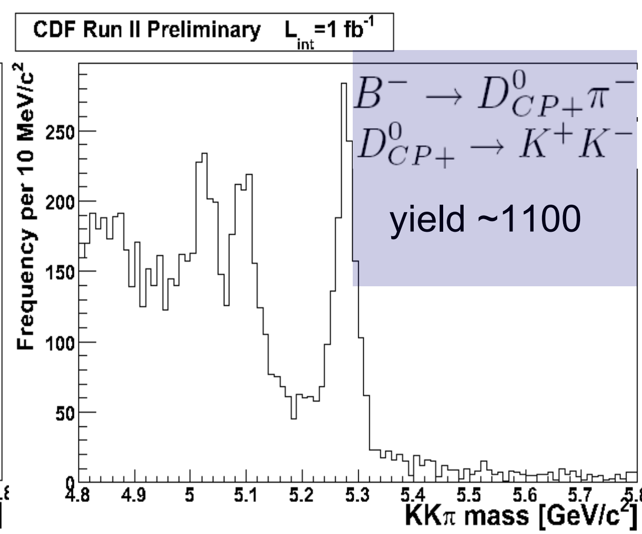
$D^0_{CP+} \to K^+K^-$

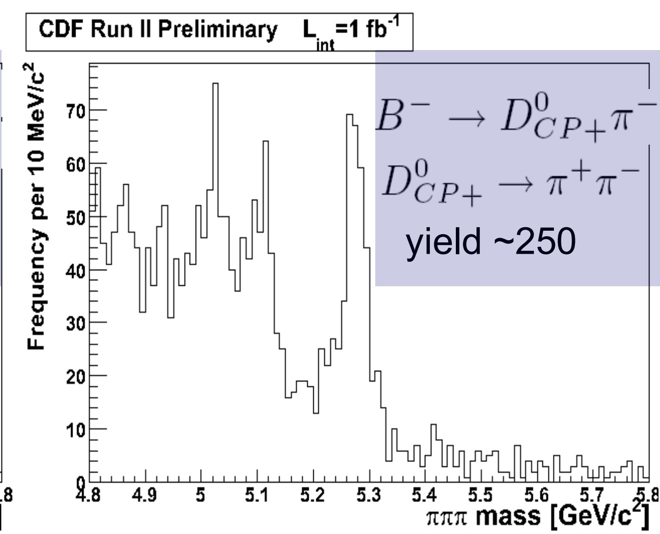
$D^0_{CP+} \to \pi^+\pi^-$

Flavor eigenstate:

$D^0 \to K^-\pi^+$



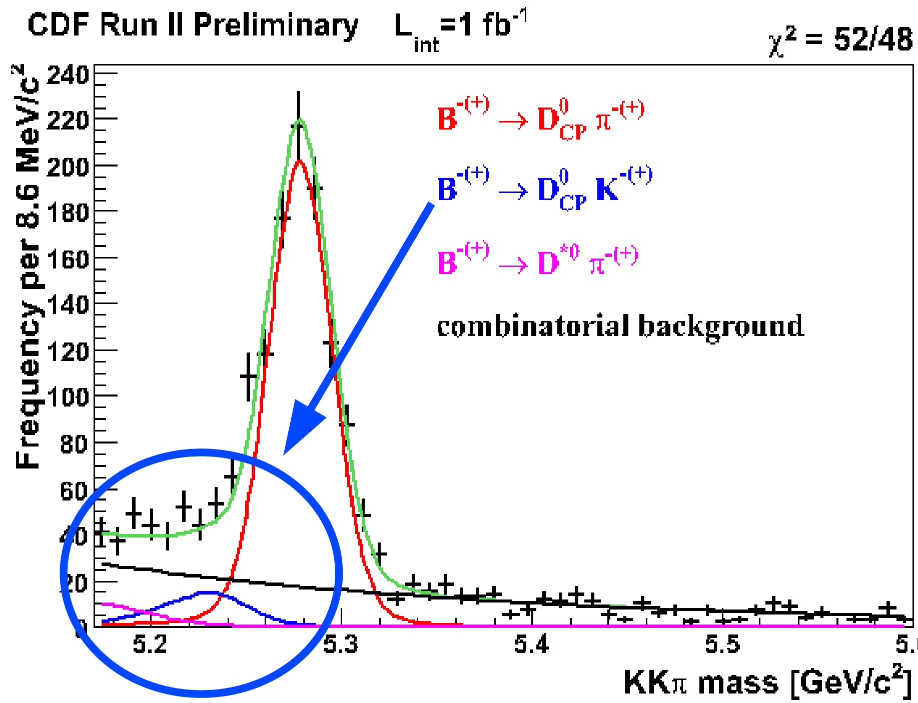


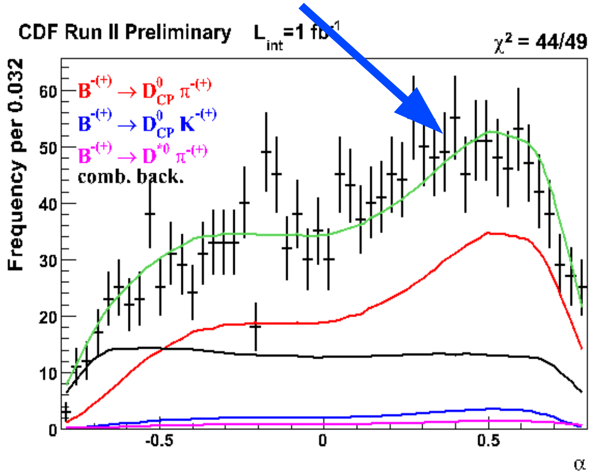


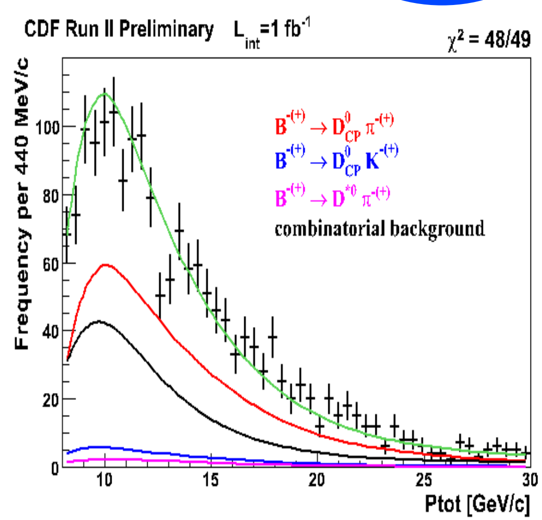
BR's and Acp in $B^+ \to D^0 K^+$

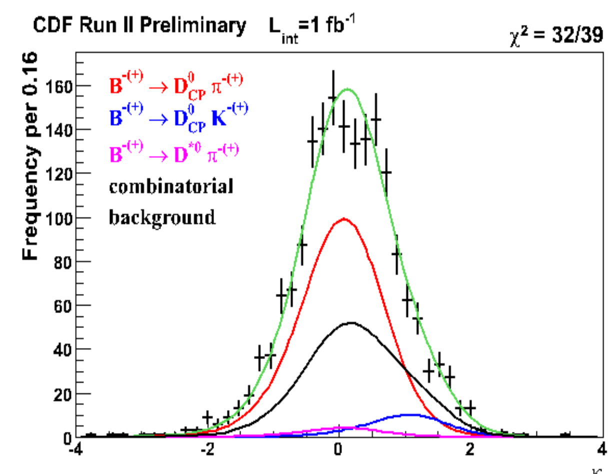
- Apply the same trick to $B^+ \to D^0\pi^+$ and $B^+ \to D^0K^+$ decays

- α distribution stops being symmetric (D is much heavier)









- But, the same approach works here as well!

BR's and Acp in $B^+ \rightarrow D^0 K^+$

- Results:
  - ratio of branching fractions:

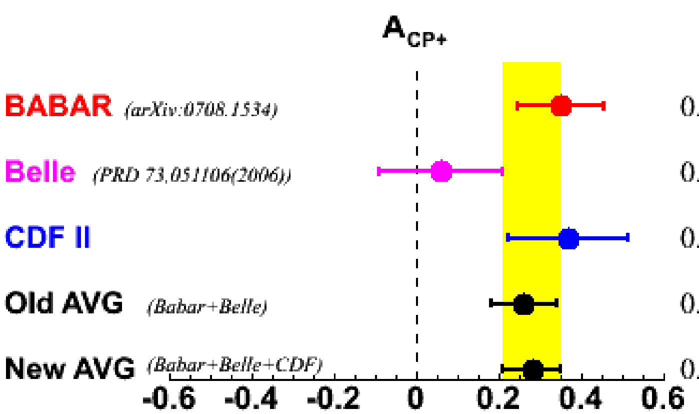
$$R = \frac{BR(B^- \to D^0 K^-) + BR(B^+ \to \overline{D}^0 K^+)}{BR(B^- \to D^0 \pi^-) + BR(B^+ \to \overline{D}^0 \pi^+)} = 0.0745 \pm 0.0043(stat.) \pm 0.0045(syst.)$$

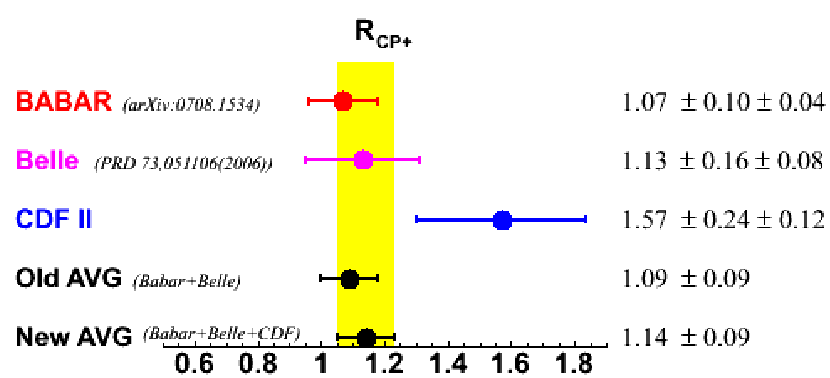
$$R_{CP+} = \frac{BR(B^- \to D^0_{CP+} K^-) + BR(B^+ \to D^0_{CP+} K^+)}{[BR(B^- \to D^0 K^-) + BR(B^+ \to \overline{D}^0 K^+)]/2} = 1.57 \pm 0.24(stat.) \pm 0.12(syst.)$$

  - direct CP asymmetry:

$$A_{CP+} = \frac{BR(B^- \to D^0_{CP+} K^-) - BR(B^+ \to D^0_{CP+} K^+)}{BR(B^- \to D^0_{CP+} K^-) + BR(B^+ \to D^0_{CP+} K^+)} = 0.37 \pm 0.14(stat.) \pm 0.04(syst.)$$

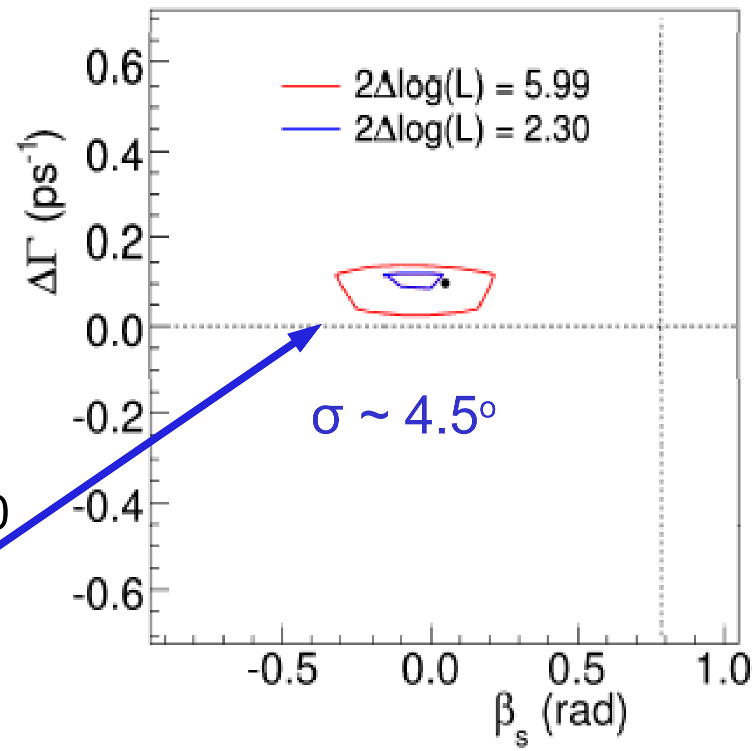
- Quantities measured for the first time at hadron colliders
- Results in agreement and competitive with B factories





Conclusions

- Very rich B physics program at Tevatron and CDF
  - Competitive with but also *complementary to* BaBar and Belle
  - Excluded a large domain of $\beta_s < 0$
- Great Tevatron performance
  - keep accumulating data
  - keep updating analyses
    - work hard to update of $B_s \rightarrow J/\psi\phi$ for the summer
    - properly combine likelihoods with D0
  - expect 6 fb-1 by the end of Run2



- This is an exciting time to work on CP violation and search for new phenomena in *B* decays!

Backup Slides

Rare decays

- With 2.0 fb^{-1}, best limit in:

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ (4.7×10^{-8}) at 95(90)%CL
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-8}$ (1.5×10^{-8}) at 95(90)%CL

arXiv:0712.1708

- 0.9 fb-1

$B(B^+ \to \mu^+\mu^-K^+) = (0.60 \pm 0.15 \pm 0.04)\times10^{-6}$,
$B(B^0 \to \mu^+\mu^-K^{*0}) = (0.82 \pm 0.31 \pm 0.10)\times10^{-6}$
consistent with world average and competitive with best measurements

$B(B_s \to \mu^+\mu^-\varphi)/ B(B_s \to J/\psi\varphi) < 2.61(2.30)\times10^{-3}$ at 95(90)%CL best limit

http://www-cdf.fnal.gov/physics/new/bottom/061130.blessed_bmumuh/

- First observation of $\overline{B}_s^0 \to D_s^{\pm} K^{\mp}$ in 1.2 fb^{-1}

109 +/- 9 signal events with ~8 sigma significance
Measure branching fraction relative to Cabibbo allowed mode:

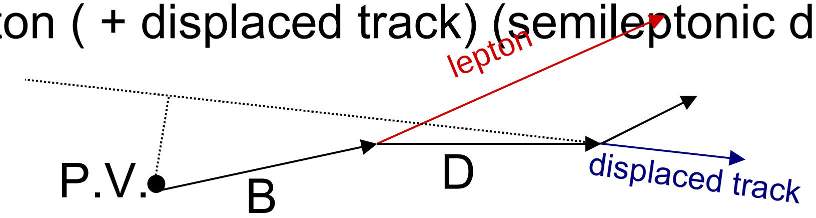
$$\mathcal{B}(\overline{B}_s^0 \to D_s^{\pm} K^{\mp})/\mathcal{B}(\overline{B}_s^0 \to D_s^{+} \pi^{-}) = 0.107 \pm 0.019(\mathrm{stat}) \pm 0.008(\mathrm{sys})$$

http://www-cdf.fnal.gov/physics/new/bottom/070524.blessed-Bs-DsK/

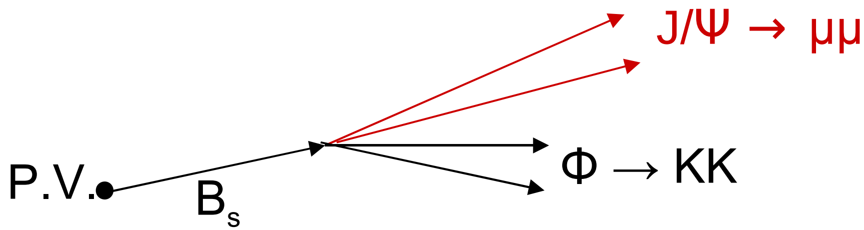
Triggers

- Triggers designed to select events with topologies consistent with B decays:

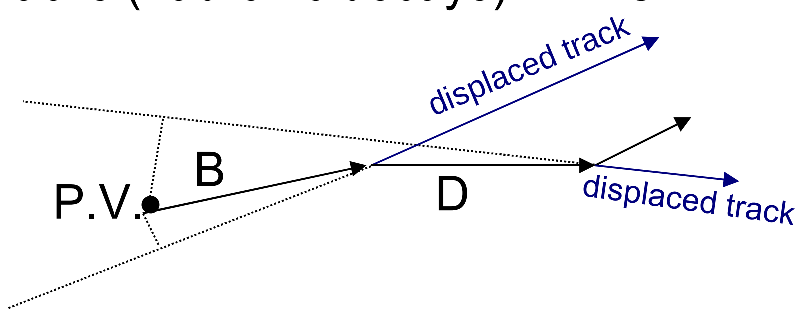
  - single lepton (+ displaced track) (semileptonic decays) ← DØ (CDF)



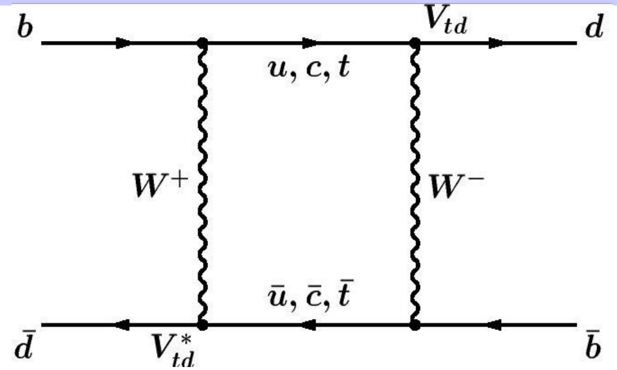
  - di-lepton (B → J/Ψ, B → μμ, B →μμ + hadrom) ← both CDF and DØ



  - displaced tracks (hadronic decays) ← CDF



Flavor tagging refresher

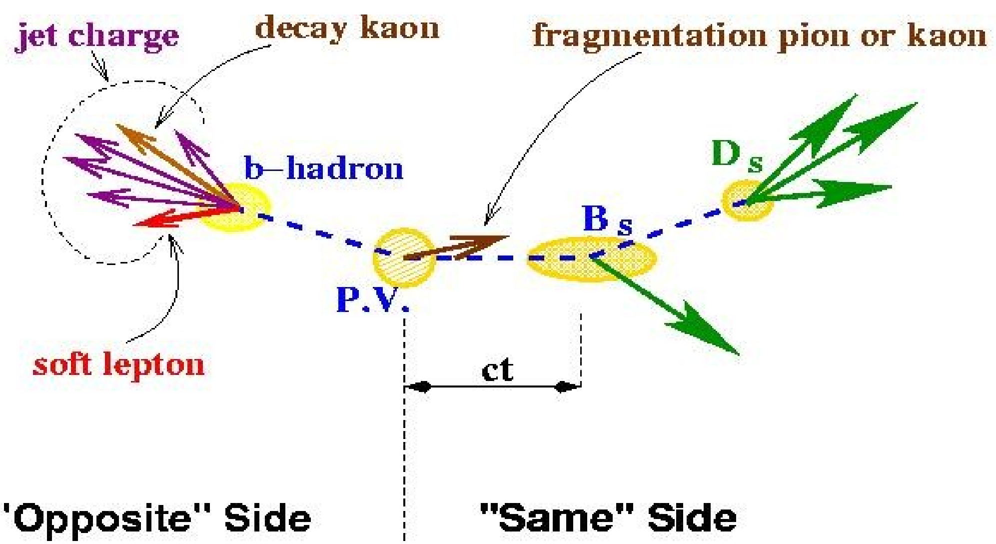


- Flavor asymmetry (from B mixing)

$$A(t) \equiv \frac{N_{\text{unmix}} - N_{\text{mix}}}{N_{\text{unmix}} + N_{\text{mix}}} = D\cos\Delta m_s t$$

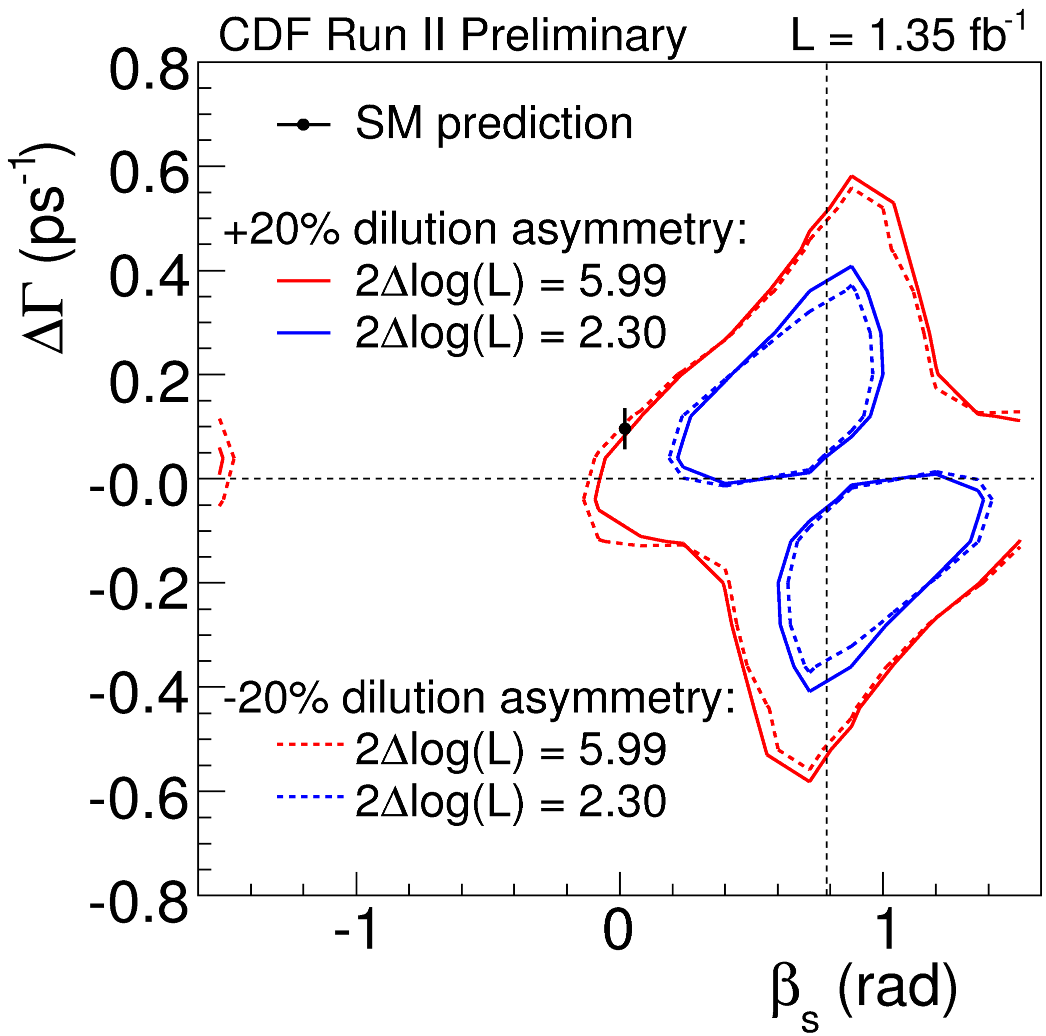
- To measure mixing:
  - Flavor at production (via "flavor tagging")
  - Flavor at decay
  - $ct \equiv L_{\text{xy}} \frac{m}{p_T}$

- Flavor tagging characterized by:
  - efficiency ε and dilution D (= 1 - 2w)
  - Statistical power ~ εD^2



Effect of Dilution asymmetry on β_s

- Effect of 20% b-bbar dilution asymmetry is very small



$B_s \to J/\psi\phi$ phenomenology

- $B_s \to J/\Psi\Phi$ decay rate as function of time, decay angles and initial B_s flavor:

$$\frac{d^4P(t,\vec{\rho})}{dtd\vec{\rho}} \propto |A_0|^2\mathcal{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathcal{T}_+ f_2(\vec{\rho})$$
$$+ |A_\perp|^2\mathcal{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathcal{U}_+ f_4(\vec{\rho})$$
$$+ |A_0||A_\parallel|\cos(\delta_\parallel)\mathcal{T}_+ f_5(\vec{\rho})$$
$$+ |A_0||A_\perp|\mathcal{V}_+ f_6(\vec{\rho}),$$

time dependence terms

angular dependence terms

terms with β_s dependence

$$\mathcal{T}_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \eta\sin(2\beta_s)\sin(\Delta m_s t)],$$

terms with Δm_s dependence due to initial state flavor tagging

$$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

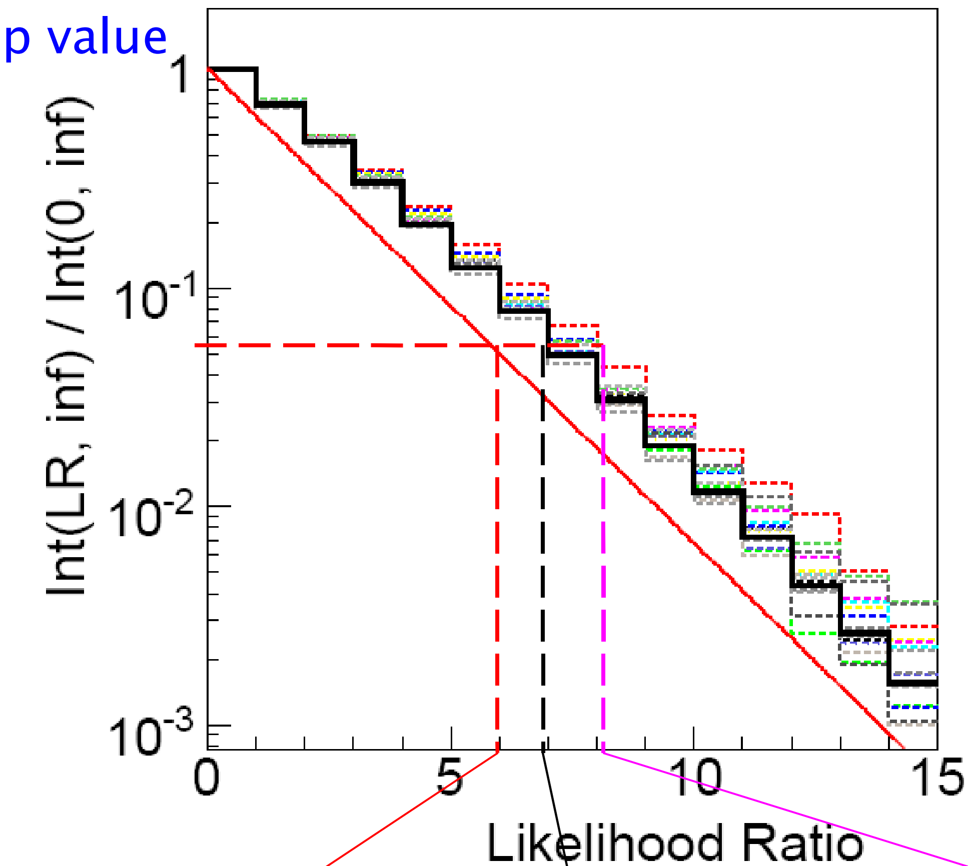
$$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)].$$

'strong' phases:

$$\delta_\parallel \equiv \arg(A_\parallel^* A_0)$$
$$\delta_\perp \equiv \arg(A_\perp^* A_0)$$

- Tagging $\to$ better sensitivity to β_s

Systematics



Red curve:

regular likelihood profile: $\chi^2(2)$

Black histogram:

average LR distribution from FC

Dashed histograms:

16 Variations of 27 nuisance parameter within 5σ with FC

Perfect likelihood

FC profile

FC profile with systematics

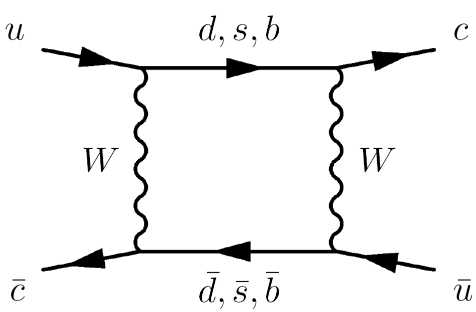
D^0 Mixing

arXiv:0712.1567

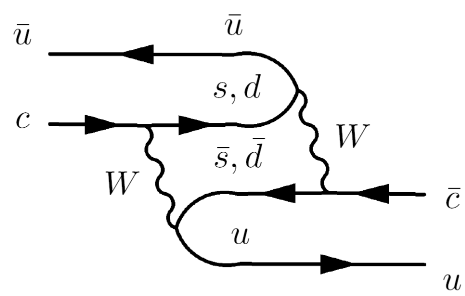
- After recent observation of fastest neutral meson oscillations in B_s system by CDF and DØ $\rightarrow$ time to look at the slowest oscillation of D^0 mesons ☺

- D^0 mixing in SM occurs through either:

'short range' processes (negligible in SM)



'long range' processes



	$\Delta M/\Gamma$	$\Delta\Gamma/\Gamma$
K^0	0.474	0.997
B^0	0.77	<0.01
B_s	27	0.15
D^0	< few%	< few%

- Recent D^0 mixing evidence $\leftarrow$ different D^0 decay time distributions in

Belle
$D^0 \rightarrow \pi\pi$, KK (CP eigenstates) compared to $D^0 \rightarrow K\pi$

BaBar
doubly Cabibbo suppressed (DCS) $D^0 \rightarrow K^+\pi^-$ compared to Cabibbo favored (CF) $D^0 \rightarrow K^-\pi^+$
(*Belle* does not see evidence in this mode)

Evidence for D^0 Mixing

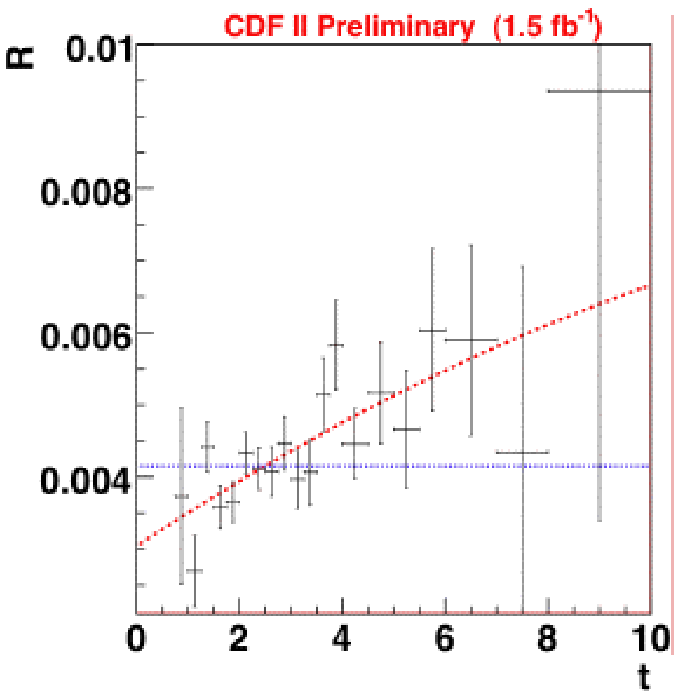
- CDF sees evidence for D^0 mixing at 3.8σ significance by comparing DCS $D^0 \to K^+\pi^-$ decay time distribution to CF $D^0 \to K^-\pi^+$ (confirms *BaBar*)
- Ratio of decay time distributions:

$$R(t/\tau) = R_D + \sqrt{R_D}y'(t/\tau) + \frac{x'^2 + y'^2}{4}(t/\tau)^2$$

where $x' = x \cos\delta + y \sin\delta$ and $y' = -x \sin\delta + y \cos\delta$

δ is strong phase between DCS and CF amplitudes

mixing parameters $x = \Delta M/\Gamma \quad y = \Delta\Gamma/2\Gamma$ are 0 in absence of mixing



Fit type	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$	χ^2 / d.o.f.
Unconstrained	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	19.2 / 17
Physically allowed	3.22 ± 0.23	6.0 ± 1.4	0	19.3 / 18
No mixing	4.15 ± 0.10	0	0	36.8 / 19

Experiment	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$	Mixing Signif.
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
BABAR	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$	2.0